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THE PSYCHOLOGICAL REVIEW

ON THE RELATION BETWEEN SIMILARITY AND TRANSFER OF TRAINING IN THE LEARNING OF DISCRIMINATIVE MOTOR TASKS [1]

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INTRODUCTION

It has long been recognized that the amount of transfer of training which takes place between one learning task and another depends upon the similarity of the tasks. A generally accepted rule is that in order to assure a high degree of transfer from one learned activity to a second, the first task must be made to resemble the second closely. The experimental studies which have been made of this relationship, however, have not arrived at conclusions which are in unanimous agreement with this point. Although some studies have indeed shown that transfer increases in amount as the two tasks are made more similar, there are some which have shown that increasing the similarity between tasks has the opposite effect of decreasing the amount of transfer. The existence of a conflict in these results seems to indicate that the factors in the situation which have been varied in similarity may not have been adequately identified or controlled in the different studies. At any rate, the principles which have emerged from these experimental studies do not at present permit the consistent prediction of transfer effects from a knowledge of the nature of the two tasks which are to be learned.

The present paper examines the concept of similarity as it applies to the transfer of training between motor skills requiring the acquisition of two or more discriminative habits. In contrast to the usual statement of the relation between similarity and transfer, it is here proposed that transfer between such tasks may best be understood in terms of the similarity among the stimuli and among the responses *within* each of the tasks to be learned, rather than *between* the elements of the first and second tasks (5, 13). It is contended that the attempt to vary the similarity of stimuli or of responses from one task to another

[1] The formulation presented in this article grew out of research under Contract N7onr-316, Task Order I, between the Special Devices Center, Office of Naval Research, and Connecticut College. The paper is a condensed version of Report No. 316-1-5 under that contract.

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usually brings about variations in similarity among the elements within the task. If these changes in similarity within the task are understood in the manner to be described, they provide a basis for the prediction of transfer from one task to another.

It will be shown that variation between a first task and a second in the transfer situation can be brought about in a number of ways: (a) by making the elements within the second task more alike; (b) by making the elements within the second task more unlike; (c) by displacing the elements within the second task in the same direction along a scale of similarity; and finally (d) by reversing the relationships between the stimuli and responses in the second task. Our analysis will attempt to show that the first three kinds of variation may be expected to result in positive transfer between the two learning tasks by an amount which is related to the degree of such variation. Reversal, on the other hand, will be shown to be the condition of negative transfer, the amount of which in turn depends upon the degree of similarity of elements within each task.[2]

One concept to be used in accounting for the relationship between similarity and transfer is the gradient of stimulus generalization (7, 9). We assume that when an individual acquires a response to a given stimulus situation, he tends to make the same response in other situations which are similar to the original one. For present purposes similarity is defined in terms of subjects' judgments. It is assumed that as stimuli become decreasingly similar, the strength of generalized response tendencies between them will also decrease. In human learning situations we are probably never dealing with a purely *primary* gradient (10), but with a gradient whose form is partly determined by secondary or mediated generalization built up by a common verbal (or other internal) response to two different stimuli (such as two different "reds"). As Gibson's (5) results show, gradients of generalization undergo a progressive reduction in range as training is continued, *i.e.*, as the required discriminations become more firmly established (8).

Although the evidence for its usefulness is scanty, we propose also to use the concept of the response generalization gradient. We assume that when an individual learns a specific response to a given stimulus, he also acquires tendencies to make similar responses to the same stimulus, such tendencies decreasing in strength as the degree of similarity between the responses and the original learned response decreases. In the case of responses, a definition of similarity is sought in terms of the results of movement rather than in characteristics of the muscular activity itself. For purposes of the present analysis, responses are conceived to vary in the aspects of direction, distance, force and rate, and similarities between them are discussed with reference to these characteristics as they apply to the movement of a single body member. As in the case of stimulus generalization, it is assumed that the effect of continued training is progressively to narrow the range of the response generalization gradient, making the responses to different stimuli more and more distinctive.

[2] It should be noted that it is not intended to describe a quantitative theory of transfer. The assumptions to be made in arriving at the principles which we shall describe are not novel ones, but have been used to varying extents by other authors (4, 6, 15, 12). We are interested only in discovering the implications of some of these basic assumptions for the problem of the relation between similarity and transfer in discriminative motor learning.

TRANSFER RELATED TO VARIATION IN THE MOTOR LEARNING TASK

The Effects of Stimulus Variation on Transfer

It should now be possible to apply these concepts to a situation which involves the acquisition of discriminative motor habits. In order to illustrate the factors which may be subjected to variation in a motor learning task in which differential responses are made to discriminated stimuli, a simple example will be used which seems capable of representing in its elements a variety of motor skills. Our standard task is one in which a subject is required to learn to make a manual response to a key located on the right on the appearance of a red stimulus light, and to make a response with the same hand to a key located on the left on the appearance of a green light. In the discussion which follows, this constitutes the *first task,* on which the subject receives a moderate amount of training. He then proceeds to learn a second task in which the stimuli are altered in the ways to be described. Figure 1 is intended to illustrate the stimulus generalization gradients surrounding each of these stimuli at the beginning of learning the second task. For our purposes stimuli are considered to vary along the color dimension.[3]

1. *Increasing the similarity of the stimuli in the second task.* This sort of variation may be illustrated by the following example: First task: red light —right key; green light—left key. Second task: orange light—right key; yellow-green light—left key. The response tendencies established by training on the initial task, and consequently assumed to be present at the beginning of learning the second task, are pictured in Fig. 1. The strengths of the measured responses to orange and yellow-green stimuli are determined by the differences between "correct" and "incorrect" generalized response tendencies in each case. There exist strong tendencies to make "correct" responses to the stimuli of the second task which are counteracted to a slight extent by tendencies to make "incorrect" responses to these same stimuli. The result of training, as indicated by the effective strengths of the responses, is that the learning of the second task begins with the desired responses already partially established. The general effect of this type of change may be summarized as follows: ***When the stimuli of the second learning task are made more similar to each other than those of the first learning task, the result is positive transfer decreasing in amount with increased similarity among the stimuli within the second task.***

As the stimuli of the second task are made increasingly similar with respect to those present in the initial task, it is evident from Fig. 1A that there will be not only decreasing "correct" response tendencies, but at the same time increasing strengths of "incorrect" response tendencies. A smaller difference between these conflicting tendencies would consequently result in smaller effective response strengths and a smaller amount of positive transfer. It is evident that this process of making the stimuli more alike in the second task may theoretically be carried to the point at which the stimuli are no longer discriminable, and the resulting transfer approaches zero.

2. *Decreasing the similarity of the stimuli in the second task.* This sort of variation may be illustrated by the following example: First task: red light

[3] The units of color differences shown in the figure have been assumed to be equal for purposes of illustration only. Within the range shown it is known that judgments of similarity correspond to the spectral order, but the units of judged similarity have not been determined.

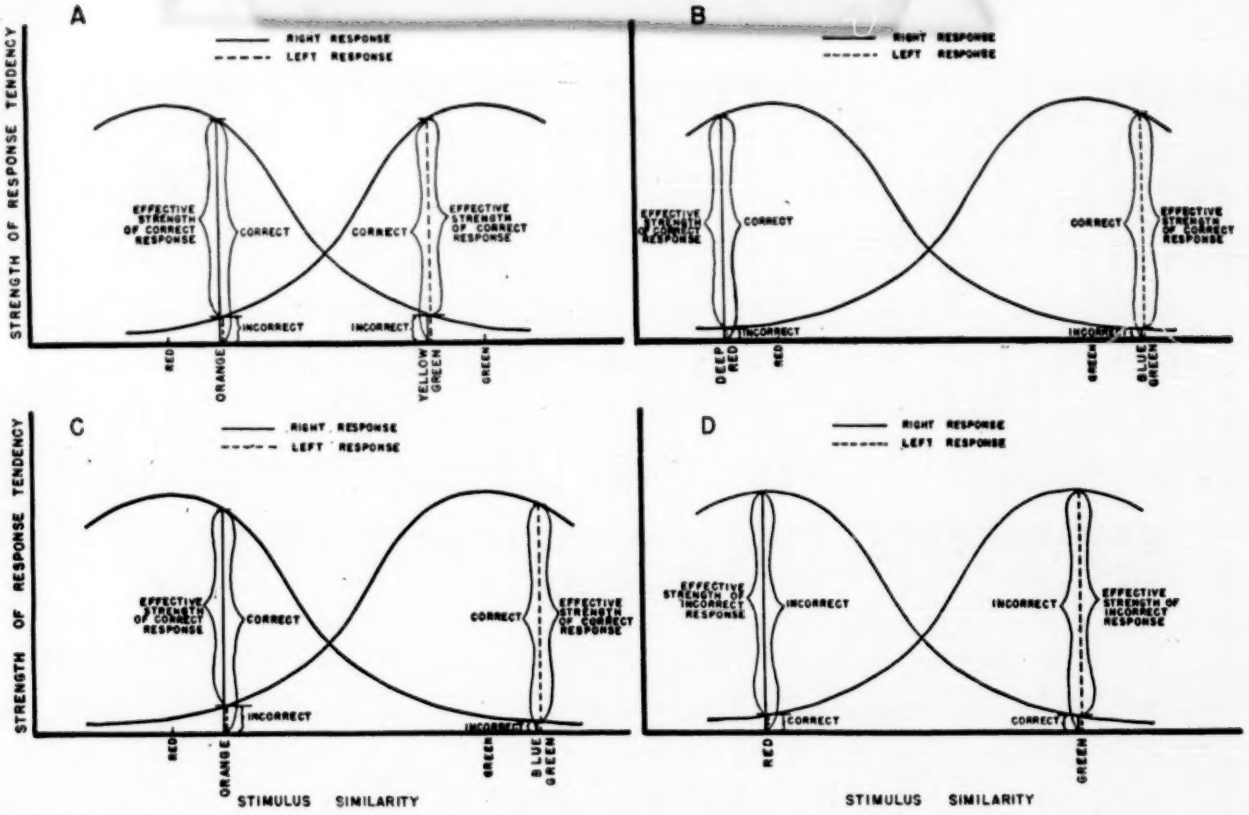

FIG. 1. Expected strengths of response tendencies, and resultant strengths of correct and incorrect responses occurring in a shift from an initial discrimination task to a second task in which the stimuli are altered. In each case it is assumed that the subject has had a moderate amount of training on the task RED—Right Response; GREEN—Left Response. A: Expected tendencies at the start of the learning of a second task in which the associations to be acquired are ORANGE—Right Response; YELLOW-GREEN—Left Response. B: Expected tendencies at the start of the learning of a second task in which the associations to be acquired are DEEP RED—Right Response; BLUE-GREEN—Left Response. C: Expected tendencies at the start of the learning of a second task in which the associations to be acquired are ORANGE—Right Response; BLUE-GREEN—Left Response. D: Expected tendencies at the start of the learning of a second task in which the (reversed) associations to be acquired are GREEN—Right Response; RED—Left Response.

—right key; green light—left key. Second task: deep red light—right key; blue-green light—left key. In terms of Fig. 1B, this kind of change means that the subject begins to learn the second task with strong response tendencies to the "correct" keys, which are counteracted by relatively weak "incorrect" response tendencies. The effective strengths of the right-key response to deep red and the left-key response to blue-green are again obtained by subtracting the conflicting tendencies in each case. This situation in which the stimuli are made less similar in the second task in contrast to the previously described situation in which they are made more similar, results in considerably weaker "incorrect" response tendencies. Making the stimuli less alike in the second task may therefore be expected to produce even greater positive transfer than making the stimuli more alike, assuming an equivalent degree of change in stimulus similarity in each instance. Figure 1B indicates that the transfer decreases more gradually than is the case with transfer resulting from increasing stimulus similarity (as shown in Fig. 1A). Consequently, with decreasing similarity of the stimuli in the second task, the transfer comes to depend almost entirely upon the strengths of the generalized "correct" response tendencies. The following statement summarizes this situation: *When the stimuli of the second learning task are made less similar to each other than those of the first learning task, the result is positive transfer decreasing in amount as the degree of similarity among the stimuli of the second task is decreased.*

3. *Altering each of the stimuli in the same direction along a scale of similarity.* This kind of variation is illustrated by the following example: First task: red light—right key; green light—left key. Second task: orange light—right key; blue-green light—left key. As illustrated in Fig. 1C, this situation has some interesting characteristics which distinguish it from those previously described. When the color of one light is changed from red to orange, this orange stimulus not only differs from red, but is at the same time in some degree more similar to green, the stimulus originally associated with a different response. In contrast, when the color of the green light is changed to blue-green, the blue-green color is similar to green but does not approach red in similarity. Thus the learning of the response to the blue-green light in the second task would be facilitated to a greater extent than the learning of the response to the orange light, because of the existence in the former case of a relatively weaker "incorrect" response tendency. Presumably this difference would be revealed in the learning of the second task by the occurrence of a greater number of errors to the orange light than to the blue-green light.[4] This situation may be summarized in the following statement: *In proceeding to a second task from the learning of a first task, transfer decreases with increasing degrees of displacement of the stimuli in the same direction along a scale of similarity.*

4. *Stimulus alteration involving mediated similarity.* The stimuli employed

[4] For the sake of brevity we limit our consideration of displacement to cases which involve relatively small changes in the stimulus. As the amount of displacement increases, the stimulus to be associated with the right key response in the second task becomes increasingly similar to the stimulus previously associated with the left key, a situation in which the "incorrect" response tendency to this stimulus outweighs the "correct" response tendency. Transfer predictions for this situation depend upon considerations to be described later in connection with *reversal*. Displacement includes the type of alteration which occurs in experiments on transposition behavior, and our analysis of it bears some resemblance to Spence's (15).

in a motor task may be replaced by other stimuli which are related, not because they fall along some physical scale, but because previous training has associated them with identical responses. The outstanding example is the case of verbal stimuli consisting of the appropriate "names" for the actual stimuli which make up the motor learning situation. The importance of this kind of stimulation for human subjects is shown by their frequent verbalization in learning motor tasks.

The extent to which transfer will occur between a motor task with stimuli such as lights and a task in which only the "names" for these stimuli are presented would seem to depend upon the extent to which previous training has established habitual connections between a light stimulus and the verbal response of its "name." Presumably the individual will tend to react in the same way to the verbal stimulus "red" as to the stimulus provided by a red light, because in the past both of these have been habitually associated with a verbal response which in turn provides a conditioned stimulus. It seems evident that stronger associations are established between some kinds of physical stimuli and their naming responses than others, thus producing differences in transfer effects.

The existence of these mediating stimuli also has a significant effect on transfer between two motor tasks. When two stimuli are equivalent because of their association with a common verbal response, transfer is expected to occur; but its extent cannot be accurately predicted without a previous measurement of the degree to which such mediating effects are present in any given situation. We have proposed that this measurement may be made by determining the similarity between stimuli by means of subjects' judgments which are assumed to reflect the degree to which the stimuli have been practiced with a common verbal response. This proposal implies that the shape of the gradient of generalization must be measured in terms of similarity judgments before predictions of transfer can be made with any degree of accuracy.

5. *Varying the number of discriminable aspects of stimulation.* A motor task may be altered by reducing or increasing the number of discriminable aspects of the stimuli which are to be associated with different responses. If, in our now familiar example, the red light were on the right side of the stimulus panel and the green on the left, a reduction in the number of discriminable aspects of the stimuli would be effected if the second task involved simply white lights in right and left positions. On the other hand, increasing the number of discriminable aspects of stimulation may be illustrated by means of the following second task: Square red light on right—press key on right; circular green light on left—press key on left.

It is supposed that each individual aspect of stimulation which has entered into training has generated its own gradient of generalization similar to those which have been described in the previous section. It seems reasonable to assume that the degree of similarity between stimuli decreases with the number of stimulus aspects which form the bases for the discrimination. Thus the task which requires different responses to stimuli differing only in color is assumed to be a more difficult task than one which requires the same responses to stimuli which differ from each other in shape and size as well. In such a case a smaller degree of overlapping between the generalization gradients would be expected, and weaker "incorrect" response tendencies are assumed to exist for each of the stimuli concerned.

With this arrangement we are able to speak of making the stimuli of a task more similar or less similar to each other by reducing and increasing, respectively, the number of discriminative aspects of stimulation provided by each. The implications to be drawn from this sort of analysis correspond with those outlined in a previous section. We should again expect the increase in similarity, in the sense of reducing the number of discriminative aspects of stimulation, to result in positive transfer which decreases as the stimuli are made more alike. We should also expect a high degree of positive transfer to result from making the stimuli of the second task more different by increasing the number of differential cues provided by each, because of the relatively weak interfering response tendencies established by training on the initial task.

The Effects of Response Variation on Transfer

The assumption of gradients of response generalization leads to conclusions concerning the relation between response similarity and transfer which are in many respects the same as those which follow from our analysis of stimulus similarity. It is supposed, for example, that when a subject acquires differential responses of 4 ounces and 12 ounces to two different stimuli, he also acquires *tendencies* to react with similar but unidentical degrees of force to the same stimuli. The effect on transfer of response variation from a first task to a second is also conceived to be analogous to the effect of stimulus variation. (a) A second task may be altered from a first task by increasing the similarity between the differential responses to be acquired. The resulting transfer would be expected to be positive and to decrease in amount as the responses were made more alike. (b) The responses of the second task may be made less similar to each other than those of the first. Again positive transfer, decreasing in amount as the responses are made less alike, is the result to be expected. (c) The responses of the second task may be displaced in the same direction on a scale of similarity. Such a change would also be expected to yield transfer in accordance with the propositions of the previous section, *i.e.*, transfer would decrease in amount with increasing degrees of displacement.

The responses within the second task may be made more alike or less alike than those within the first by changing the *number* of differential aspects which they possess. For example, if the first task required responses differing from each other in both direction and in force, the second task might require responses which differ in force only, thus making the responses more similar to each other. In accordance with our previous analysis we should expect positive transfer to decrease to the extent that these responses have been made more similar to each other in the second task. It will be recognized that an example could readily be given to illustrate the case in which responses are made less similar to each other in the second task by adding some characteristic which was not present in the responses of the first task. Again transfer would be predicted in accordance with the analogous instance of stimulus variation.

Perhaps the most important thing to point out regarding the transfer effects of variation in responses from one task to another is that we are *not* led to conclude that different results are obtained by varying stimuli alone and by varying responses alone. The Wylie hypothesis (16) predicts positive transfer when responses remain constant and stimuli are varied and negative transfer

when stimuli remain constant and responses are varied. In contrast to this, the present hypothesis states that when stimuli are maintained constant, variations in the similarity of the responses within a task produce positive transfer just as do variations in similarity of stimuli when responses are held constant. The conditions which lead to negative transfer, on the other hand, are conceived to involve a type of variation called *reversal* which cannot be described fully in terms of similarity between responses. The conditions of reversal are described in a following section.

One type of response variation which is not extensively considered here involves requiring the subject to make responses in the second task with an entirely different body member. In such instances, provided the stimuli of the two tasks remain the same, positive transfer may be expected. Studies have shown, for example, considerable degrees of positive transfer of motor tasks between such members as the right and left hands (3), or the hand and foot (1, 3). Presumably such transfer occurs because these responses are highly similar even though they do involve different members. Whether this similarity exists because of previous learning or because of some kind of innate neural organization, we make no attempt to answer here. Another reason why we are led to expect positive transfer between body members is simply because of the fact that the stimuli of the two tasks remain identical. The effect of practice on the first task is consequently to make the stimuli become more and more distinctive, and this effect carries over to the second task even when the responses required in that task make use of entirely different parts of the body. Our reasoning in this instance is essentially the same as that of Gibson (4), who discusses this phenomenon as stimulus *pre-differentiation.*

Transfer Effects of Reversing Stimulus-Response Relationships

It is now necessary to introduce a type of task variation which is different in a fundamental sense from those previously considered. Up to the present we have dealt with situations in which certain kinds of changes are brought about in stimuli associated with given responses, or with changes in responses associated with given stimuli. The type of variation which we wish to describe here, however, arises when we ask the subject in the second task to learn to associate a given stimulus with a response which has previously been associated with another stimulus of the same task. In terms of our standard example the situation would be represented as follows: First task: red light—right key; green light—left key. Second task: red light—left key; green light—right key. This transfer situation involves *complete reversal* of the stimulus-response relationships in proceeding from the first task to the second. Figure 1D represents the expected results at the beginning of the learning of the second task. It will be seen that the learner begins this task with a tendency ("correct" for this task) to make a left-key response of nearly zero strength to the red light, and with the tendency to make the right-key response of considerable strength (now "incorrect") to the red light. Likewise the tendency to make the right key response ("correct" for this task) to the green stimulus is of nearly zero strength, whereas the tendency to make a left-key response (now "incorrect") is great. This means that the subject begins to learn the second task with the considerable handicap of strong interfering ("incorrect") response tendencies. It is easy to under-

stand that under such conditions he will not learn the task as rapidly as he would if he had not had any previous training on the first task, *i.e.*, the resulting transfer is negative. Although situations of this sort have not been systematically investigated in studies of motor learning, somewhat comparable conditions occur in the studies of Hunter (11) and Bunch (2), in which animals first learned one maze pattern and were subsequently required to learn a pattern whose correct turns were exactly reversed. In both these studies large amounts of negative transfer were found. Our conclusion is that reversal of the stimulus-responses relationships within a discrimination learning task is the typical condition for negative transfer. The results of complete reversal may be summarized as follows: *When the stimuli and responses of the second learning task are identical with those of the first learning task, but the relationships between these stimuli and responses are reversed, the result is a maximum amount of negative transfer.*

One important characteristic of the situation which involves *complete* reversal is that it makes little difference whether the responses have been reversed or the stimuli reversed. One can say either that the subject is required, in the second task, to learn to make the same responses to reversed stimuli, or that the subject is required to learn to make reversed responses to the same stimuli.

Because of the general acceptance of equivalence between the terms, it is important to emphasize the distinction between *interference* and *negative transfer* which this discussion implies. We conceive of interference as the likely result whenever incorrect response *tendencies* are present. Thus in the previously described situation of making the stimuli more similar to each other in a second task, the degree of interference which occurs was seen to depend upon the degree to which the stimuli were made more alike, and would be measured by an increase in errors or by a decrease in response time. In that situation, however, the over-all effect, despite the interference, was seen to be positive transfer. It is only when the incorrect response tendencies become greater in amount than the correct response tendencies that we expect to get negative transfer. In such a case the learning of a second task is interfered with to so great an extent that the rate of learning is slower than the learning of the same task would be without previous training on an initial task. Thus, the experimental meaning of *negative transfer* is *a reduction in rate of learning, following practice on a previous task, below the rate which would have been achieved without any previous practice.*

The transfer situation may be set up in such a way that the two tasks vary in the *degree* to which they approach this condition of complete reversal. Such situations are referred to as *partial reversal*. Let us suppose again that the original task is one which presents the following discrimination: red light—right key; green light—left key. Suppose, then, that we altered this to a final task like this: orange light—left key; yellow-green light—right key. It is evident that in such a situation the subject is required to learn to make reversed responses to stimuli which are highly similar to the original ones, thought not identical with them. It will be realized from an examination of Fig. 1D that at the beginning of the learning of the second task the "incorrect" response tendencies to the orange light and the yellow-green light would in this case far outweigh the "correct" response tendencies to the same stimuli. It is expected, therefore, that negative transfer would be the result, *i.e.*, that

TABLE I

SHOWING THE TYPES OF VARIATION WHICH MAY BE MADE IN A SECOND LEARNING TASK WITH RESPECT TO A FIRST LEARNING TASK, AND THE TRANSFER EXPECTED TO RESULT FROM EACH

Type of variation in second task	Stimuli of second task	Responses of second task	S-R relationships of second task	Transfer
Stimulus alteration	increasingly similar	identical	identical	positive, decreasing in amount
	increasingly dissimilar	identical	identical	positive, decreasing in amount
	same degree of similarity, increasingly displaced[5]	identical	identical	positive, decreasing in amount
Response alteration	identical	increasingly similar	identical	positive, decreasing in amount
	identical	increasingly dissimilar	identical	positive, decreasing in amount
	identical	same degree of similarity, increasingly displaced[5]	identical	positive, decreasing in amount
Complete reversal	identical	identical	reversed	maximum negative
Partial reversal	increasingly similar, increasingly dissimilar, or increasingly displaced	identical	reversed	negative, decreasing in amount
	identical	increasingly similar, increasingly dissimilar, or increasingly displaced[5]	reversed	negative, decreasing in amount

the training on the first task would hinder rather than aid the learning of the second. It will also be evident that as the stimuli to be associated with reversed responses become more alike, the smaller will be the "incorrect" tendencies, and consequently, the smaller the amount of negative transfer. Zero transfer is approached as the response tendencies to correct and incorrect keys become more equal and tend to cancel each other out. This conclusion may be summarized as follows: *When the stimuli of the second learning task are made more similar to each other than those of the first learning task, and the responses are reversed, the result is*

[5] Transfer predicted from this type of variation is conceived to hold only for relatively small amounts of stimulus change. See footnote 4.

negative transfer decreasing in amount as the similarity between stimuli is increased.

It is hoped that our discussion up to this point has made clear the prediction that the reversal of stimulus-response relationships leads to negative transfer. Moreover such reversal is to be contrasted in its effect upon transfer with the kind of change in the internal similarity of a task which maintains the same relationships between the stimuli and responses. Table I provides a summary of the conclusions which have been arrived at in accordance with this hypothesis, and serves at the same time to emphasize the differences between the conditions of positive transfer and negative transfer. The table contains descriptions of the different ways in which the elements of a second task may be altered with respect to those of the first. The transfer which is predicted to follow each specific kind of change, in accordance with our hypothesis, is shown in the final column. As a general summary it may be said that when S-R relationships remain *identical,* the greater the amount of alteration of the elements of the task the smaller will be the positive transfer; when S-R relationships are *reversed,* the greater the amount of alteration of the elements of a task, the smaller will be the amount of negative transfer.

DISCUSSION

Although our analysis has for reasons of clarity been confined to discriminative learning situations in which the responses are accomplished by movements of the skeletal muscles, its reasoning may be applied with little change to the learning of verbal responses by the paired-associate method. It is not our intention to emphasize a distinction between motor learning of the type we have been describing and paired-associate verbal learning. On the contrary, we consider them to be quite identical in their essential aspects. Not only do we feel that the same principles of learning apply to both, but the importance of self-instructional stimuli has been sufficiently emphasized to indicate that the learning of discriminative motor responses cannot be completely understood without a consideration of the kind of verbal reaction which the human subject displays when he learns a motor task. Space prevents the presentation of specific implications of this hypothesis to the problem of transfer in the learning of paired associates. It may be suggested, however, that in many studies of this problem, inter-task variation has brought about uncontrolled variations among the elements within each task.

Our discussion has confined itself to motor tasks of a relatively simple sort: those in which the subject is required to make one motor response to one stimulus, and a different response, using the same body member, to a second stimulus. It is recognized that a relatively small proportion of actual motor skills are as simple as this. In fact it is usually with regard to more complex skills that the question of transfer arises. Nevertheless we believe that our analysis forms the basis on which investigations of transfer in these more complex skills must rest. It is evident that the usual source of complexity in motor skills of this type lies in the increase in *number* of discriminative habits which the individual is required to learn. Thus it is common to find that an operator must acquire skill not simply in pressing two different keys in response to two different lights, but rather in making 15 or 20 different responses to as many different stimuli.

The way in which learning and transfer vary with the number of discriminative responses of the task is an impor-

tant problem in the field of motor learning, comparable to that which concerns the factor of amount of material (or length of list) in studies of verbal learning. There is obviously a need for investigation of the relationships between variation in number of discriminative responses and difficulty of learning, as well as the relation between number of responses and transfer. However, it is our belief that experiments which are designed to attack these problems will need to take into account the intra-task similarities of both stimuli and responses, as they have been discussed here. In a task in which 10 different responses must be acquired to 10 different stimuli, any given stimulus of the total set is more or less similar to any of the other 9 stimuli, and any given response is more or less similar to the other 9 responses. If one were to study transfer with such a task in a situation in which all 10 stimuli were to be altered to some degree, it is our contention that the alteration must be defined in terms of changes in the similarity among the 10 stimuli of the task itself in order for meaningful relationships between alterations and transfer to be found. An initial hypothesis to be applied to experimental studies of such complex skills might well be that the generalization tendencies of the responses to each stimulus summate in a simple algebraic manner with the gradients associated with the other stimuli of the total set. Also, conceiving of transfer as falling on a continuum, the positive and negative transfer effects predicted for the separate discriminative habits may be expected to summate algebraically, allowing for prediction of the net transfer result of stimulus and response variations.

The conflict between the conclusions of the present analysis and the Wylie hypothesis (16) has already been pointed out. According to the present set of principles, positive transfer is to be expected from changes in either the responses or the stimuli, or both, provided that these changes do not involve *reversal* of the relationships of stimuli to responses within the task. A contrast may also be noted between these predictions and the Skaggs-Robinson hypothesis (14). Whereas the latter predicts a low point in transfer when the first and second tasks are dissimilar to some unspecified degree, and increasing transfer beyond this point of dissimilarity, our hypothesis predicts that the amount of positive transfer will progressively decrease with greater degrees of alteration in the similarity of elements *within* a task. In place of the idea that a minimum point in transfer is reached and passed as the similarity of the first and second tasks decreases, the hypothesis of the present paper conceives the low point in transfer (maximum negative transfer) to be attained by the manipulation, not of similarity, but of a *different variable*—stimulus-response relationships.

It is not at all evident that our hypothesis makes predictions which are new in a practical sense. Many individuals are able to make perfectly good rough predictions of the kind of transfer to be expected from a given type of change in a learning task. Thus it does not come as a surprise to most people to learn that the typical condition of negative transfer is one of reversal, or that positive transfer is the usual result when the stimulus or response aspects of one task are similar to those of another. At the present time, though, few results of controlled experiments can be adduced in support of the more specific implications of these hypotheses. The reason for this lack of evidence lies in the fact that experiments on transfer have not been carried out under conditions which have permitted

the control and systematic variation of the variables which are conceived in our analysis to be operating in the transfer situation. It is our hope that future experiments will be designed specifically to test the predicted effects of these variables on transfer.

SUMMARY

An analysis is made of the implications for transfer of alterations in the stimuli and in the responses of discriminative motor learning tasks. It is contended that these alterations are most clearly stated in terms of the similarities existing among the stimuli and among the responses of each task, rather than in terms of similarities between tasks. Four main types of alteration are described: (a) making the stimuli (or responses) of the second task more alike than those of the first; (b) making the stimuli (or responses) of the second task less alike than those of the first; (c) displacing the stimuli (or responses) of the second task, relative to those of the first task, in the same direction along a scale of similarity; and (d) reversing the stimulus-response relationships of the second task in relation to what they are in the first task. With the use of the concept of the *gradient of generalization,* conceived as applicable to both stimulus and response, the results of each of these types of alteration are related by hypothesis to positive and negative transfer effects. Certain further implications of the hypothesis for the design of experimental studies of transfer in paired-associate verbal learning, and in complex motor skills of the discriminative type, are also discussed. It is believed that the principles arising from this analysis provide a useful framework for the statement of the relationships of "similarity" to transfer.

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A STIMULUS–RESPONSE ANALYSIS OF THE HOARDING HABIT IN THE RAT

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INTRODUCTION

In spite of the early theoretical emphasis on habits as "chained reflexes" psychologists have spent relatively little time in actual *experimental* analysis of complex and heterogeneous learned activities. With scattered exceptions the more analytic experimental work has centered on fairly simple and homogeneous types of responses like bar-pressing and maze-running. The choice of such responses is of course to be largely explained by the greater control that is possible with them and the expectation that the relationships between the basic variables may thus be more effectively treated. As a consequence, however, general synthesizing principles have been more or less neglected.

The hoarding habit of the laboratory rat seems to afford a particularly good opportunity for investigation of behavior synthesis. It is the primary purpose of the present study to utilize the common learning principles derived from basic animal experimentation in the interpretation of this more complex and heterogeneous habit. The hypothesis will be advanced that the hoarding behavior pattern can be most adequately explained as an *integrated series* of heterogeneous learned responses.

In the previous paper in this series (19) an attempt was made to place the hoarding behavior of the laboratory rat in the usual framework of the psychology of learning, and to present preliminary observational evidence in support of the view that this behavior is a function of learning, rather than of innate factors as has been generally held. Before summarizing certain of the more important aspects of that evidence a brief orienting review will be presented for those readers not already familiar with the special literature of the hoarding studies.

Hoarding Studies and Previous Interpretations

The strong propensity of the laboratory rat to carry food pellets about in its cage is readily observed by anyone familiar with the typical rat colony. Experimental study of this behavior tendency, however, has been restricted to the last ten years or so during which a number of studies of "hoarding" or "food-storing" have been reported. In the great majority of these the animal has been confined for varying periods of preliminary accommodation in a small individual living cage, usually with some degree of food deprivation introduced as a factor. In the hoarding test proper the rat is given access to an alley leading away from the cage and to a bin full of food pellets (or similar transferable materials). The number of pellets returned to the cage within an arbitrarily fixed testing period (usually thirty minutes daily) is recorded as a measure of the hoarding activity of the animal. Under the conditions of the usual experiment this behavior begins more or less slowly but is gradually accelerated. In extreme cases an animal may spend most of the thirty minute period scurrying back and forth with pellets until as many as fifty or sixty are accumulated in the cage. Not only has there been a wide variety of investigations into the more relevant variables presumably influencing such food-carrying behavior (3, 4, 5, 24, 25, 26, 41, 44, 46, 47, 51) but the hoarding activity itself has been used as a dependent variable in studies of "frustration" (17, 22) and the adult effects of infantile deprivation (15, 16, 23, 45).

Little progress has been made towards an adequate theoretical interpretation of hoarding. The most recent attempt has been by Bindra (5) who postulates "shyness" and "security" as the relevant variables. Although this appears to point in a promising direction it does not clearly state the particular factors that produce hoarding. By far the most popular type of explanation advanced has been some variation of the thesis that hoarding has an instinctive basis. This has resulted largely from the expressed inability of the investigators (*e.g.*, **25**, p. 667, and **46**, p. 53) to see how the usual rewards could operate to reinforce the hoarding behavior in well-fed rats which return pellets regularly but fail to feed on them. The most explicitly formulated version of this point of view may be found in Morgan's paper, "The Hoarding Instinct" (30), but it is clearly evident in other reports and appears to be the orthodox view of the naturalistic type of observer. Although the manifest non-explanatory nature of such an instinct hypothesis need not be labored, Morgan's own excellent comment, from another context, may be usefully cited: "The principle most often followed in practice, it seems, is that of calling any behavior instinctive which is somewhat complicated and *whose mechanisms are not understood by the observer.* Instinctive behavior, therefore, gets defined in terms of the ignorance of the observer" (**29**, p. 396).

Observational Basis of Present Interpretation

In the previous paper (19) data were presented from a number of simple, orthodox hoarding experiments utilizing food pellets, wooden blocks, and milk pellets (cotton dental plugs saturated with fresh milk). The data, appropriately analyzed, gave evidence not only of learning but also of generalization, discrimination, extinction, resistance to extinction, and spontaneous recovery. Negatively accelerated learning and extinction curves were found, despite the complications introduced by the arbitrary design of the typical hoarding experiment (such as the fixed thirty minute test period with no control of important variables like amount of feeding in the cage following the return of each pellet, the number of pellets returned per daily period, etc.). Moreover, careful observations and objective recordings of the time and extent of the first movements of the *naive* rat into the alley gave striking evidence of a distinctly hierarchal development of the early exploratory—and *pre-hoarding*—behavior. The animals were observed to make a large number of preliminary, partial entrances into the alley before reaching the bin end, and typically to make one or more excursions to the bin before returning with the first pellet. A certain amount of direct feeding on the pellet—and presumably corresponding reinforcement—was also observed to occur following the first few pellet returns. The subjective impressions of the observers that the onset of hoarding was an active learning process were supported by the objective data. Failure of previous investigators to find similar empirical evidence for the primary role of learning was suggested to be a function of their failure to make adequate efforts to find it, and particularly of their failure to make the relevant observations of the pre-hoarding and early hoarding phases of the behavior.

THEORETICAL INTERPRETATION

A major postulate of this paper is that the typical hoarding habit may be primarily explained as the result of the fusion of independently acquired habits. These will first be described separately, after which consideration will be given to the problem of their integration.

1. *Pre-experimental Responses to Food Pellets*

In all the hoarding experiments thus far reported, with the exception of a part of the original one by Wolfe (**51**), the rats had apparently been maintained on food pellets at some time prior to their introduction to the hoarding situation. Although this condition has been recognized as a possible factor

in the later development of hoarding behavior (51, 46), no attempt has been made to treat it in a systematic or analytic manner. In the present analysis three salient aspects of the rat's pre-hoarding responses to the food pellet as a stimulus have been differentiated and will be considered in turn.

a. *Pellet seizure.* The pellet-seizure response is prominent in the behavior repertoire of the laboratory rat under normal living conditions, and is particularly marked in rats living in groups. Typically, upon the introduction of new food pellets or the re-discovery of old ones, the rat may be observed to grasp the pellet in its mouth and carry it about rather than to start to feed upon it at once. As the first component in the usual cage eating sequence, therefore, the pellet-seizure response may be expected to be strongly reinforced by the subsequent drive reduction associated with actual feeding behavior. Moreover, it may also be expected to be reinforced, more directly, by the *response-produced* stimulation that invariably follows jaw muscle contractions, including those which are actually involved in direct feeding. A similar kind of *immediate* secondary reinforcement has been suggested by Spence (43) and experimentally indicated by Grice (11) in their treatment of the problem of delayed reward in visual discrimination learning in the rat.

There is also the possibility of some kind of *direct* sensory "reinforcement" from the (mainly) olfactory stimuli produced by the food pellet, as suggested by Young (52) in his recent theoretical interpretation of the work on food preference and palatability. Bash's (1, 2) work on responses to food in rats with neurophysiologically isolated intestinal tracts offers further indirect support for this supposition, although it is also susceptible of explanation in accordance with the principles of secondary reinforcement. It is this sort of "reinforcement" which may be responsible for the primary approach responses of animals to certain pre-potent types of stimulation. In so far as it is based on inherited sensory structures and is, presumably, independent of previous experience, such a response in its early appearance may be said to be innately determined. Subsequent activation of it, however, and especially subsequent modification and integration with other responses, are clearly functions of learning.

Additional sources of reinforcement for the pellet-seizure response will be suggested in the following discussion.

b. *Pellet carrying.* After seizing a food pellet the rat typically carries it about the cage. Such running responses, with food pellets grasped in the jaws, are particularly evident in rats caged in groups. But they are also found even in the individually caged rat, which tends to seize the pellet whether offered by hand or dropped into the cage, and carry it to a back part of the cage. So strong is this tendency, as a matter of fact, that it is regularly observed to occur, although with reduced intensity, even in rats on unlimited feeding schedule and at times when a pellet is routinely selected from an ample supply of pellets which have been in the cage for some hours.

The running response following pellet-seizure may be interpreted as having been originally made to the frightening stimuli associated with the providing of the pellets (noise, sight of the feeder's hand and body, etc.) or, in the social situation, with the active competition for the pellets by other animals. A recent report by Calhoun (7) suggests the important role of competition in the securing of food by trapped wild rats living in a one hundred foot square pen with a central food source. Vigorous attempts by one rat to take a pellet out of another's jaws are clearly demon-

strated in a film by Mowrer (33). In accordance with orthodox learning principles the stimulus situation associated with the arousal of such emotional reactions may be expected to re-arouse them—in the milder form of "anxiety" —upon subsequent occasions (32, 34, 35, 36, 20, 27, 9). Thus the running response would tend to be conditioned to the kinesthetic stimulation produced by the pellet seizure.

Empirically the rat is observed to persist in its running activity with the pellet until a relatively "safe" place has been reached, that is, until the fear-arousing and action-inducing cues are sufficiently reduced. The consequent anxiety-reduction serves to reinforce the earlier pellet-seizure response as well as the running response, in the behavior sequence initiated by pellet recognition, and may continue to do so even after the originally effective threatening stimuli have become inoperative (20, 27, 9).

c. *Pellet release.* In animals having previous experience with food pellets the pellet-release response, like the pellet-seizure and pellet-carrying responses, is acquired prior to the hoarding test. It is obviously impossible for a rat to feed on a pellet as long as the pellet is firmly held by the jaws. Release of the pellet is therefore a necessary component of the usual behavioral sequence in normal cage feeding. In a hungry animal this occurs quickly after a position of relative seclusion has been reached. Nibbling upon the pellet is usually either carried out directly while it rests on the cage floor or with the aid of the forepaws after it has been reduced to smaller pieces. The act of releasing the pellet may thus be considered to be conditioned to the proprioceptive stimulation associated with the cessation of movement and to be reinforced by the more or less immediately occurring direct feeding with resultant drive reduction.

In summary: *Prior to the first hoarding test the experimentally naive rat has acquired a strongly reinforced sequence of responses initiated by pellet recognition and involving the seizure, carrying and eventual release of the food pellet.*

2. *Pre-hoarding "Homing" Habit*

The observations previously reported (19) gave the unmistakable impression that in the course of its preliminary explorations in the alley the naive rat was forming a strong tendency to leave and return into the cage. While the rat was in the alley, particularly in the early training stages, any unusual stimulus was likely to result in a quick return into the cage. The alley excursions were observed gradually to lengthen until the rat reached the bin area, soon after which it generally began to return with pellets.

The rapid development of this habit of leaving and returning to the cage, clearly evident before the actual onset of hoarding, may be simply but adequately explained upon the basis of the secondary reinforcing properties of the various stimuli produced by the cage (mainly olfactory and visual) and previously associated with such primary need reduction as has been effected by regular eating and drinking in the cage. In earlier hoarding studies (26, 47) it has been shown that "familiarity" with the cage, mainly dependent upon olfactory and visual factors, is a most important determinant of hoarding, which is not easily induced in rats newly placed in strange cages.

With the assumption of such secondary reinforcing properties it is not difficult to understand why sudden external stimuli should send the freely exploring rat quickly back into the cage, as was consistently observed in our experiments. In the absence of any obvi-

ous strong external stimulation the mild but mounting "tensions" accumulating from the influx of new stimuli in the alley would eventually also send the animal in the direction of familiar, anxiety-reducing cues—thus resulting in an apparently "spontaneous" return to the cage.

Bindra's recent report (5) of greatly accelerated hoarding activity following the substitution of "open" alleys for "closed" ones is especially suggestive in this connection. He reports that in the "open" situation the animal also took considerably more time to enter the alleys. Although further behavioral details were not reported in this study it may be supposed, on the basis of our own observations, that the increment in hoarding followed the strengthened tendency to return to the cage, once the rat had entered the alley. A similar interpretation may be made of the greatly accelerated hoarding induced by exceptionally strong lighting of the alley—but not of the cage—in an unpublished study by Stellar (45; also cited by Morgan in 30).

In summary: *Even before it has reached the bin end of the alley, and thus prior to the onset of hoarding, the naive rat in the typical hoarding experiment has developed the habit of leaving and returning to the home cage.* It should be emphasized that this observation is empirically grounded and independent of any particular theoretical interpretation, although the one given above appears to be satisfactory.

Note on exploratory behavior. Although for the purpose of this analysis the universally observed exploratory tendency of the rat may be simply assumed, it is nevertheless an interesting and theoretically important problem. In the present situation the particularly important role of direct olfactory cues is suggested. Unless the alleys have been thoroughly washed following each hoarding test—and this has not been mentioned in the reports—a certain amount of exploration may be accounted for on the basis of residual, cumulative food and animal odors. The secondary reinforcement resulting from such stimulation may thus be suggested as a possibly significant factor in the appearance of exploratory behavior. Visual cues from the bin end of the alley may also be mentioned as possible factors, but in view of the relatively poor visual abilities of the rat it is not likely that they are important in this respect.

3. *Integration of the Hoarding Habit*

The problem of the fusion of these independently learned habits into the integrated hoarding habit is resolved by assumption of a *dual stimulating and reinforcing* role for the food pellet. The following discussion outlines the main relationships.

a. *First hoarding activity.* When the exploring rat finds the binful of food pellets at the end of the alley it behaves entirely in accordance with previous habit formation. One of the pellets is seized, more or less promptly, depending upon the current drive state of the animal, and carried quickly back to the cage. Certainly no new explanation is needed for this response. The pre-experimental habit of carrying the food pellet about in the cage is reactivated under new anxiety conditions. The animal moves in the direction of anxiety-reducing cues, as it has *learned* to do previously both within and without the cage, and the result is that the pellet is returned to the cage. Release of the pellet follows the cessation of movement, as previously, and the first pellet-return response is completed.

Following the first two or three releases of the pellet in the cage the rats in our experiments were typically observed to spend at least a small amount of time in active nibbling, again in accordance with their previous habit formation. The extent of this feeding

largely depended upon the deprivation condition of the animal. In his early study Hunt (15) noted that there appeared to be a conflict between eating and hoarding responses. For this reason it has been customary to allow partial satiation before the hoarding test proper, in order to accelerate the onset of hoarding behavior. Although the theoretical significance of this early feeding behavior does not appear to have been recognized, it may be expected to have a direct reinforcing influence on the preceding sequence of responses, in the same manner as it previously did within the cage. This suggestion is supported by the observations made previously (19) on hungry rats which quickly shifted their feeding positions to the alley when the pellet was removed *immediately* after its return into the cage.

Once the first return with a pellet has been completed and its immediate feeding motives satisfied, the rat tends to re-enter the alley and return to the bin at regularly decreasing time intervals (19). The role of the food pellet as a *secondary reinforcer* now becomes apparent. The strong olfactory and visual stimuli produced by the food pellets may be suggested as the most probable factors in the reinforcement of the bin-return component of the hoarding habit. It is also possible that the proprioceptive stimulation resulting from pellet-seizure exerts some influence in this respect, in addition to reinforcing more directly the pellet-seizure response itself.

A small amount of nibbling, as well as sniffing, of the food pellets has been observed at the bin. Rapid return to the bin under such conditions would be easily explained on the basis of reinforcement principles, and the situation would be somewhat similar to that in the Columbia Obstruction method of measuring drive. The main difference is that whereas in the latter situation the animal is arbitrarily returned to the starting box by the experimenter, in the hoarding test it returns because of the strong habits previously established.

b. *Subsequent development of hoarding.* The typical negatively accelerated shape of the learning curves in our previous hoarding study (19, Figs. 2, 3, 4) may be explained upon the basis of the accumulation of reinforcement under the new conditions to which the rat was exposed. Successive reinforcements of the bin-return response would be expected to result in an increasing tendency to make this response to the stimulus cues produced by the open alley. Successive reinforcements of the cage-return response would similarly operate to strengthen that tendency. The empirical evidence from many other hoarding studies (*cf.* 4, 25, 26, 31, 46, 47) is thoroughly in accord with these expectations. The rat that has begun to hoard generally increases the vigor and speed of its food-carrying activity until in extreme cases a remarkable amount of work may be accomplished. For example, we have observed one female rat which returned a peak total of 97 pellets over the forty-inch runway in thirty minutes—an average of more than one complete trip every twenty seconds. Similar examples of excessive hoarding activity have been reported elsewhere (*e.g.*, 25, p. 666, footnote). There can be no doubt that the bin and its contents exert a strong influence upon the behavior of the rat which has had the relevant preliminary and early hoarding experiences.

The subsequent decrement in hoarding behavior is readily explicable on the basis of a progressive accumulation of inhibitory factors associated with the effortfulness of the activity (42). Negatively accelerated extinction curves were found in our previous study (19,

Figs. 5 and 6) and other earlier work (26, 31, 47).

c. *Role of food deprivation.* The development of hoarding behavior may be interpreted, in accordance with the preceding discussion, as a result of a certain balance between the feeding and the anxiety-reducing motives. So far as feeding motivation is concerned, the optimal condition appears to be one in which recent deprivation has been followed by partial satiation. As suggested above, this important point has been appreciated in a practical, if not in a theoretical, sense.

The more rapid development of strong hoarding habits in recently deprived rats is probably in part a function of their higher activity level with consequent acceleration of the preliminary exploratory behavior and development of the cage-return habit. An additional factor favoring the more rapid development of hoarding behavior in these animals would be the differential activation of the jaw-manipulating responses that have been conditioned to the sight and smell of the food pellets. Data from the observations previously reported (19) support this interpretation in that the non-deprived animals made over three times as many pelletless trips to the bin preceding their first pellet return as did the recently deprived animals.

Enhancement of the stimulating properties of the food pellet through "frustration" is also suggested by the experiment of McCord (22), in which hungry animals were permitted to see and reach for small food pellets kept out of reach behind a wire mesh barrier. Such animals subsequently seemed to remove a greater number of pellets from a clip in the side of the cage than the controls, equally under-fed but not subjected to the additional "frustration." A similar result seems to have been obtained by Wolfe (51) in young rats which had been placed for a period of twenty days on an "inadequate" diet—one sufficient merely to maintain their body weight at a time when it would normally have been increasing.

It may also be pointed out that although operation of the secondary reinforcing factors of the kind postulated above is dependent upon previous activation of response systems by relatively high drive states there is no requirement that such states be currently active. Experimental demonstrations of this point have been provided by Brogden (6), and by Saltzman and Koch (38). Brogden's results seem particularly pertinent to the present situation in that completely satiated dogs continued to make the instrumental response which brought them food, in the conditioning situation, even though they then refused to eat the food.

d. *Special conditions.* In Wolfe's (51) study some rats were raised on powdered food, and were significantly retarded in hoarding behavior on the first test day. The appreciable increment in hoarding shown on the subsequent test days may be explained on the basis of a relatively rapid learning of responses to the food pellet. Approach and manipulatory responses would be expected on even the first encounter of such rats with a food pellet. They would result from the generalization to be expected on the basis of the olfactory and visual (texture) similarity between the food pellets and the powdered food, and would account for the slight amount of first day hoarding which Wolfe found. Subsequent reinforcement of the kind postulated above would explain the further development and integration of the hoarding habit.

It should also be mentioned that the present analysis, while directly applicable to the typical hoarding situation, would need to be modified to fit special

circumstances. For example, when the pellets are placed within the home cage, as has been done in certain of the early studies on "frustration" (17, 22), obviously the "homing" habit would not be involved. Learned pellet-seizure, pellet-carrying, and pellet-release tendencies would be necessary, however, in treating such cases. In certain other hoarding studies (25, 51) in which the distance to the food bin was considerably shortened, it is probable that the pre-hoarding exploratory behavior was much reduced and that pellet returns followed more quickly upon the first alley entrances. These cases may be considered as simplifications, in this respect, of the typical hoarding situation, rather than as exceptions to the basic pattern. The use of longer alleys seems to have facilitated our observations by throwing into sharper relief the behavioral origins of the activity.

4. *Instigation and Reinforcement of the Fully Developed Habit*

If the hoarding habit is formed from a fusion of previously established habits the question of its subsequent instigation and reinforcement arises. Data previously presented (19, Fig. 6) have suggested the remarkable persistence of this habit over a twelve week testing period in animals on unlimited feeding and thus, presumably, minimal hunger drive. In view of the high effortfulness of the activity its strong resistance to complete extinction suggests the operation of correspondingly strong instigating and reinforcing agents. Three specific sources of these may be suggested.

a. *Regular reinforcement from feeding responses.* The fact that the animals necessarily continue to make characteristic feeding responses suggests that the secondary reinforcement from the response-produced stimulation accompanying jaw movements is periodically renewed and thus effectively maintained. Experimental demonstration of the way in which interpolated periodic association with primary reinforcement upholds the motivating power of a secondary reinforcer has recently been offered by Saltzman (37). In the hoarding situation such periodic interpolation of primary reinforcement serves to maintain not only the originally independent pellet-seizure tendency but also the secondary reinforcing powers associated with the sight and smell of the food pellets, thus helping to account for the continued instigation of the alley runs in spite of their high degree of effortfulness.

b. *Spontaneous running activity.* The kind of physical restrictions imposed by the small individual living cages typically employed in hoarding studies can be expected to encourage the universally observed tendency of the normal animal towards a certain amount of spontaneous activity. The physical dimensions of these living cages closely resemble those of the cages commonly attached to the rotating drum type of apparatus for measuring general running activity. The implication of this similarity is that the same basic factors that motivate the normal, well-fed animal toward a certain amount of spontaneous activity, in the rotating drum apparatus, may well be expected to operate in the hoarding cage. The running activity in this case of course would take place in the open alley, and would thus indirectly encourage the persistence of the food carrying behavior. The finding of maximal, or near-maximal, activity in rats following twenty-four hours of enforced inactivity (39, 40) helps to strengthen this interpretation in view of a similar schedule in the usual hoarding experiment in which twenty-three hour periods of rest are regularly interpolated in between the daily half-hour tests.

c. *Drive generalization.* Miller (28) has recently presented a theoretical and experimental analysis of the concept of drive generalization, according to which habits originally developed and reinforced under one particular set of drive conditions may be subsequently activated by a different set of drive conditions. Hull's (14) postulate 7 deals directly with this phenomenon, and related experiments besides Miller's own experimental work may be found in reports by Estes (8) and Webb (50). The implications for the present problem are clear. Food-carrying habits learned under some degree of hunger drive and food reinforcement may subsequently be activated by drive conditions which are, superficially at least, quite different. The major possibilities in the present problem appear to be thirst and sex.[1]

Evidence for the influence of thirst may be seen in the incidental observation of Hunt (15) concerning facilitation of food-hoarding in an animal accidentally deprived of water, in an experiment mentioned by Hunt (15, p. 353, footnote) but as yet unpublished, and in the later experiment of Bindra (3) in which food pellets were often returned by thirsty but well-fed animals.

The results of the previous study in this analysis (19) suggested the role of the sex drive in that consistently more hoarding was done by female rats, with their four to five day estrus cycle and associated periodic spurts of general activity (41, 48). In the experiment providing direct sex comparisons, the females regularly returned from two to three times as many pellets as the males. It may also be noted that the six rats selected as exceptionally active hoarders were females. Their persistent hoarding over a twelve week period of daily tests represented a striking resistance to complete extinction (19, Fig. 6). Comparable data are not available for males, whose hoarding scores were consistently lower.

The sex difference does not appear to have been stressed in the literature but some relevant data may also be gleaned from other studies.[2] Wolfe's original report (51) suggests a higher rate of food-carrying in female rats. Morgan, Stellar and Johnson (31) report a quicker onset and slightly more hoarding in females. A similar result was found in another experiment in our laboratory (23). A study by Miller and Postman (25) also may be analyzed for relevant supporting data.

With such periodic drive intensification associated with the estrus cycle it is not surprising that the specifically directed food-carrying activity of female rats develops to so high a level and is so markedly resistant to extinction.

DISCUSSION

Biological Implications

From a general biological point of view the major theoretical significance of the present interpretation is that it suggests the basically non-purposive and learned character of a fairly complex pattern of behavior which is commonly found in many species under natural conditions, which has long been regarded as essentially instinctive in character, and which has obvious survival value in evolution.

[1] The possibility may also be mentioned of including the skin conditions associated with low temperature in this classification (*cf.* McCleary and Morgan, 21).

[2] The single study clearly showing an opposite tendency, that of Hunt and Willoughby (17), does not bear directly on this sex distinction. This follows from the fact that the males, which hoarded almost three times as many pellets as the females, were fully grown adults (220 days of age) while the females were only 55 days of age. Since ovulation in the rat normally does not begin until about 77 days (18), estrual functions were obviously of very doubtful importance in this experiment.

In consideration of the evidence for this statement it should be remembered that there is an even greater need in the field observation than in the laboratory experiment for careful consideration of the origin of a behavior pattern. The greater difficulty involved in arranging the appropriate observations in the former case is obviously no excuse for making of generalizations based upon the adult, fully developed behavior. This general tendency of the naturalistic observer may be regarded as one important factor in his acceptance of innate determinants in hoarding behavior. It also constitutes one important reason for the value of supplementary laboratory experiments, specifically designed to delineate the critical variables. Such factors may then be assumed to operate also in the field situation to the extent that the basic conditions are correlated.

It is suggested that the basic factors are so correlated in the present phenomenon. In the case of the Pine squirrel, for example, the nests and certain nearby regions in and around the home trees are represented by the home cages of the laboratory rat; the surrounding grounds, beneath and around the home trees, are represented by the alleys in the laboratory apparatus; and the concentration of pine cones beneath the home tree, and particularly beneath other less familiar trees, is represented by the concentration of food pellets in the bin area of the alley. There is in the early life of the squirrel abundant opportunity for *learning* to leave and quickly return to the nest, particularly in response to unusual stimuli, with resultant secondary reinforcement of the sort postulated in the present analysis. There is also abundant opportunity for the squirrel, with its characteristic body structure and feeding habit repertoire, normally to *learn* to react to edible cones in basically the same way as the laboratory rat learns to react to the food pellets it finds in its environment.

Under these conditions it is not surprising that the food-carrying habit should develop so easily in the Pine squirrel, with the resultant classification of it by the layman and the naturalist as "hoarding"—often implying the deliberate storing of food materials. But it seems more reasonable to suppose that the squirrel, like the rat, is operating on a simpler set of principles and is merely responding to food materials in its characteristically learned manner where and when it happens to find them. The result is that a large number of edible materials are accumulated at various points of strongest familiarity to the squirrel, in and around the trees, and at a time of the year shortly preceding that when they will be most needed. The fact that this particular habit has very great utility to the animals showing it undoubtedly helps to explain the success of these species in evolutionary survival but bears no more direct relationship to its ontogenetic or phylogenetic origin.

A similar interpretation might be made for many if not all of the other hoarding animals. One may mention the universality of regular feeding habits involving jaw manipulations, the near universality of home regions—and consequent "homing" responses—in practically all terrestrial animals, and the prominence of contributory factors like periodic hunger and startling (mildly anxiety-arousing) stimuli. The basic factors are thus available for early fusion into food-carrying habits with subsequent reinforcement. Their high frequency of occurrence helps to explain the prevalence of varying degrees of food-storing behavior, and its unique development in animals with especially well adapted basic body structures and habits (such as the pack rat, in which

a high degree of generalization apparently occurs).

Why closely related forms (*e.g.*, certain of the common squirrels) do not show significant hoarding activity will need to be explained in terms of the particular behavioral background of each form. Special tendencies, such as the burying of food objects, would complicate but would not necessarily change the basic relationships. They would also need to be explained in accordance with corresponding factors in the animal's body structure and habit repertoire.

Psychological Implications

1. The present analysis may be considered as an additional, specific demonstration of the fundamental role played by anxiety and anxiety-reduction in the development and integration of behavior. The occurrence of threatening stimulation and consequent anxiety arousal and reduction appears to be closely knit into the formation of some of the most fundamental and useful habits. Its normal importance in animal behavior, without the experimental use of electric shock, is confirmed.

2. The fact that the present interpretation has been necessarily analytic in its treatment of the hoarding habit should not obscure the essential *continuity* of the actual behavior. The empirically observed continuity, however, may be tentatively interpreted as a function primarily of the simultaneous stimulating and reinforcing properties of certain stimuli, such as the food pellet. Postulation of such complex interrelationships and synthesizing principles appears to be necessary if the empirically observed facts of behavior are to be adequately explained in terms of the basic relationships derived from relatively simpler situations.

3. In the face of certain types of objections to analysis and "elementarism" it may be emphasized that postulation of basically mechanical—that is, lawful—operation of learning functions does not necessarily require that behavior be "blind" or "stupid." In the present analysis evidence has been presented (19) for the flexibility of behavior in accordance with changing conditions under lawful—and, therefore, predictable—relationships. A pertinent example would be the progressive shift in feeding position shown by the milk-hoarding rats as they learned to carry milk pellets decreasing distances from the bin.

Lawful operation of basic functions has been impressively demonstrated in Harlow's (12) recent paper giving evidence for the *gradual learning* of insight in primates. That particular study also seems to offer a particularly effective answer to those theorists like Hilgard (13) and Waters (49) who have recently attacked Lloyd Morgan's Canon—with its simple scientific demand for parsimony in explanation—as an obstacle in the interpretation of animal behavior. The absence of adequate data to support suspected complex functions should certainly be regarded as more of a challenge to the experimenter than to the principle of parsimony.

4. Hoarding may be tentatively classified as one of a large group of self-sustaining activities whose persistence apparently needs to be explained in terms of other motivational relationships than those originally operative (*cf.* 10). In complex habits which have been formed from other simpler and independently established habits, a certain amount of the instigation and reinforcement that accounts for their persistence may be mediated through the fused components, in the manner suggested above for the hoarding habit. That is, the apparent absence of direct motivational sources may be largely due

to a failure to recognize the *continuing* instigation and reinforcement provided by the component habit systems. Adequate analysis of such complexly integrated habits may help to explain their superficially "autonomous" persistence.

5. With respect to the vastly more complex matter of human hoarding it is tempting to make brief and cautious comment. In spite of all the obvious behavioral manifestations of cultural accretions and symbolic functions it is nevertheless conceivable that the basic pattern for at least some of the activities classed as "hoarding" is the same as that described above for the food-carrying rat. There would be, to take the most common example of money, the same early and persistent reinforcement of the various money-acquiring responses. There would also be the relatively slow extinction of these responses, for long after the original needs have been satisfied. And there would be the many new and potent types of instigation and reinforcement—many of them purely symbolic in nature—to continue to motivate the response systems. Under such circumstances it is not surprising that certain human habits of acquisition should show so marked a development beyond the requirements of original needs and so strong a resistance to extinction.

SUMMARY AND CONCLUSIONS

A theoretical interpretation is offered of the preliminary empirical observations reported in a previous paper (19) on the origin and persistence of the hoarding habit in the laboratory rat. Hoarding behavior is interpreted as a complex habit formed primarily from the fusion of the earlier and independently learned "homing" and pellet-seizure habits. Previous failures to emphasize the learned basis of this behavior pattern are considered to be primarily due to the ignoring of the early, pre-hoarding phases of the behavior and the consequent failure to make the relevant empirical observations.

Detailed explanations are suggested for the synthesis of the component habits and the origin and persistence of the more complex hoarding habit. The general concepts of secondary reinforcement, anxiety-reduction, and drive generalization are applied.

Further theoretical implications of the present analysis are discused.

The present analysis is of interest in that it specifically demonstrates the applicability of experimentally derived learning principles, with experimentally testable consequences, to more complex behavioral phenomena. Further experiments explicitly designed to test certain of the more important implications of the present analysis are in progress. It is expected that after empirical and theoretical isolation of the critical variables, and their experimental confirmation, postulation of the pseudo-explanatory concept of "instinct" will be unnecessary.

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TOWARD A STATISTICAL THEORY OF LEARNING *

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Improved experimental techniques for the study of conditioning and simple discrimination learning enable the present day investigator to obtain data which are sufficiently orderly and reproducible to support exact quantitative predictions of behavior. Analogy with other sciences suggests that full utilization of these techniques in the analysis of learning processes will depend to some extent upon a comparable refinement of theoretical concepts and methods. The necessary interplay between theory and experiment has been hindered, however, by the fact that none of the many current theories of learning commands general agreement among researchers. It seems likely that progress toward a common frame of reference will be slow so long as most theories are built around verbally defined hypothetical constructs which are not susceptible to unequivocal verification. While awaiting resolution of the many apparent disparities among competing theories, it may be advantageous to systematize well established empirical relationships at a peripheral, statistical level of analysis. The possibility of agreement on a theoretical framework, at least in certain intensively studied areas, may be maximized by defining concepts in terms of experimentally manipulable variables, and developing the consequences of assumptions by strict mathematical reasoning.

This essay will introduce a series of studies developing a statistical theory of elementary learning processes. From the definitions and assumptions which appear necessary for this kind of formulation, we shall attempt to derive relations among commonly used measures of behavior and quantitative expressions describing various simple learning phenomena.

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Preliminary Considerations

Since propositions concerning psychological events are verifiable only to the extent that they are reducible to predictions of behavior under specified environmental conditions, it appears likely that greatest economy and consistency in theoretical structure will result from the statement of all fundamental laws in the form

$$R = f(S),$$

where R and S represent behavioral and environmental variables respectively. Response-inferred laws, as for example those of differential psychology, should be derivable from relationships of this form. The reasoning underlying this position has been developed in a recent paper by Spence (8). Although developed within this general framework, the present formulation departs to some extent from traditional definitions of S and R variables.

Many apparent differences among contemporary learning theories seem to be due in part to an oversimplified definition of stimulus and response. The view of stimulus and response as elementary, reproducible units has always had considerable appeal because of its simplicity. This simplicity is deceptive, however, since it entails the postulation of various hypothetical processes to ac-

count for observed variability in behavior. In the present formulation, we shall follow the alternative approach of including the notion of variability in the definitions of stimulus and response, and investigating the theoretical consequences of these definitions.

It will also be necessary to modify the traditional practice of stating laws of learning in terms of relations between isolated stimuli and responses. Attempts at a quantitative description of learning and extinction of operant behavior have led the writer to believe that a self-consistent theory based upon the classical *S-R* model may be difficult, if not impossible, to extend over any very wide range of learning phenomena without the continual addition of *ad hoc* hypotheses to handle every new situation. A recurrent difficulty might be described as follows. In most formulations of simple learning, the organism is said originally to "do nothing" in the presence of some stimulus; during learning, the organism comes to make some predesignated response in the presence of the stimulus; then during extinction, the response gradually gives way to a state of "not responding" again. But this type of formulation does not define a closed or conservative system in any sense. In order to derive properties of conditioning and extinction from the same set of general laws, it is necessary to assign specific properties to the state of not responding which is the alternative to occurrence of the designated response. One solution is to assign properties as needed by special hypotheses, as has been done, for example, in the Pavlovian conception of inhibition. In the interest of simplicity of theoretical structure, we shall avoid this procedure so far as possible.

The role of competing reactions has been emphasized by some writers, but usually neglected in formal theorizing. The point of view to be developed here will adopt as a standard conceptual model a closed system of behavioral and environmental variables. In any specific behavior-system, the environmental component may include either the entire population of stimuli available in the situation or some specified portion of that population. The behavioral component will consist in mutually exclusive classes of responses, defined in terms of objective criteria; these classes will be exhaustive in the sense that they will include all behaviors which may be evoked by that stimulus situation. Given the initial probabilities of the various responses available to an organism in a given situation, we shall expect the laws of the theory to enable predictions of changes in those probabilities as a function of changes in values of independent variables.

DEFINITIONS AND ASSUMPTIONS

1. *R-variables.* It will be assumed that any movement or sequence of movements may be analyzed out of an organism's repertory of behavior and treated as a "response," various properties of which can be treated as dependent variables subject to all the laws of the theory. (Hereafter we shall abbreviate the word response as *R*, with appropriate subscripts where necessary.) In order to avoid a common source of confusion, it will be necessary to make a clear distinction between the terms *R*-class and *R*-occurrence.

The term *R*-class will always refer to a class of behaviors which produce environmental effects within a specified range of values. This definition is not without objection (*cf.* 4) but has the advantage of following the actual practice of most experimenters. It may be possible eventually to coordinate *R*-classes defined in terms of environmental effects with *R*-classes defined in terms of effector activities.

By *R*-occurrence we shall mean a particular, unrepeatable behavioral event. All occurrences which meet the defining criteria of an *R*-class are counted as instances of that class, and as such are experimentally interchangeable. In fact, various instances of an *R*-class are ordinarily indistinguishable in the record of an experiment even though they may actually vary with respect to properties which are not picked up by the recording mechanism.

Indices of tendency to respond, *e.g.*, probability as defined below, always refer to *R*-classes.

These distinctions may be clarified by an illustration. In the Skinner-type conditioning apparatus, bar-pressing is usually treated as an *R*-class. Any movement of the organism which results in sufficient depression of the bar to actuate the recording mechanism is counted as an instance of the class. The *R*-class may be subdivided into finer classes by the same kind of criteria. We could, if desired, treat depression of a bar by the rat's right forepaw and depression of the bar by the left forepaw as instances of two different classes provided that we have a recording mechanism which will be affected differently by the two kinds of movements and mediate different relations to stimulus input (as for example the presentation of discriminative stimuli or reinforcing stimuli). If probability is increased by reinforcement, then reinforcement of a right-forepaw-bar-depression will increase the probability that instances of that subclass will occur, and will also increase the probability that instances of the broader class, bar-pressing, will occur.

2. *S-variables.* For analytic purposes it is assumed that all behavior is conditional upon appropriate stimulation. It is not implied, however, that responses can be predicted only when eliciting stimuli can be identified. According to the present point of view, laws of learning enable predictions of changes in probability of response as a function of time under given environmental conditions.

A stimulus, or stimulating situation, will be regarded as a finite population of relatively small, independent, environmental events, of which only a sample is effective at any given time. In the following sections we shall designate the total number of elements associated with a given source of stimulation as S (with appropriate subscripts where more than one source of stimulation must be considered in an experiment), and the number of elements effective at any given time as s. It is assumed that when experimental conditions involve the repeated stimulation of an organism by the "same stimulus," that is by successive samples of elements from an *S*-population, each sample may be treated as an independent random sample from S. It is to be expected that sample size will fluctuate somewhat from one moment to the next, in which case s will be treated as the average number of elements per sample over a given period.

In applying the theory, any portion of the environment to which the organism is exposed under uniform conditions may be considered an *S*-population. The number of different *S*'s said to be present in a situation will depend upon the number of independent experimental operations, and the degree of specificity with which predictions of behavior are to be made. If the experimenter attempts to hold the stimulating situation constant during the course of an experiment, then the entire situation will be treated as a single S. If in a conditioning experiment, a light and shock are to be independently manipulated as the *CS* and *US*, then each of these sources of stimulation will be

treated as a separate S-population, and so on.

It should be emphasized that the division of environment and behavior into elements is merely an analytic device adopted to enable the application of the finite-frequency theory of probability to behavioral phenomena. In applying the theory to learning experiments we shall expect to evaluate the ratio s/S for any specific situation from experimental evidence, but for the present at least no operational meaning can be given to a numerical value for either S or s taken separately.

3. *Probability of response.* Probability will be operationally defined as the average frequency of occurrence of instances of an R-class relative to the maximum possible frequency, under a specified set of experimental conditions, over a period of time during which the conditions remain constant. In accordance with customary usage the term probability, although defined as a relative frequency, will also be used to express the likelihood that a response will occur at a given time.

4. *Conditional relation.* This relation may obtain between an R-class and any number of the elements in an S-population, and has the following implications.

(a) If a set of x elements from an S are conditioned to (*i.e.*, have the conditional relation to) some R-class, R_1, at a given time, the probability that the next response to occur will be an instance of R_1 is x/S.

(b) If at a given time in an S-population, x_1 elements are conditioned to some R-class, R_1, and x_2 elements are conditioned to another class, R_2, then x_1 and x_2 have no common elements.

(c) If all behaviors which may be evoked from an organism in a given situation have been categorized into mutually exclusive classes, then the probabilities attaching to the various classes must sum to unity at all times. We consider the organism to be always "doing something." If any arbitrarily defined class of activities may be selected as the dependent variable of a given experiment, it follows that the activity of the organism at any time must be considered as subject to the same laws as the class under consideration. Any increase in probability of one R-class during learning will, then, necessarily involve the reduction in probability of other classes; similarly, while the probability of one R decreases during extinction, the probabilities of others must increase. In other words, learning and unlearning will be considered as transfers of probability relations between R-classes.

5. *Conditioning.* It is assumed that on each occurrence of a response, R_1, all new elements (*i.e.*, elements not already conditioned to R_1) in the momentarily effective sample of stimulus elements, s, become conditioned to R_1.

An important implication of these definitions is that the conditioning of a stimulus element to one R automatically involves the breaking of any pre-existing conditional relations with other R's.

6. *Motivation.* Experimental operations which in the usual terminology are said to produce motives (*e.g.*, food-deprivation) may affect either the composition of an S or the magnitude of the s/S ratio. Detailed discussion of these relations is beyond the scope of the present paper. In all derivations presented here we shall assume motivating conditions constant throughout an experiment.

7. *Reinforcement.* This term will be applied to any experimental condition which ensures that successive occurrences of a given R will each be contiguous with a new random sample of elements from some specified S-population. Various ways of realizing this definition experimentally will be discussed in the following sections.

SIMPLE CONDITIONING: REINFORCEMENT BY CONTROLLED ELICITATION

Let us consider first the simplest type of conditioning experiment. The system to be described consists of a subpopulation of stimulus elements, S_e, which may be manipulated independently of the remainder of the situation, S, and a class, R, of behaviors defined by certain measurable properties. By means of a controlled original stimulus, that is, one which has initially a high probability of evoking R, it is ensured that an instance of R will occur on every trial contiguously with the sample of stimulus elements which is present. In the familiar buzz-shock conditioning experiment, for example, S_e would represent the population of stimulus elements emanating from the sound source and R would include all movements of a limb meeting certain specifications of direction and amplitude; typically, the R to be conditioned is a flexion response which may be evoked on each training trial by administration of an electric shock.

Designating the mean number of elements from S_e effective on any one trial as s_e, and the number of elements from S_e which are conditioned to R at any time as x, the expected number of new elements conditioned on any trial will be

$$\Delta x = s_e \frac{(S_e - x)}{S_e}. \qquad (1)$$

If the change in x per trial is relatively small, and the process is assumed continuous, the right hand portion of (1) may be taken as the average rate of change of x with respect to number of trials, T, at any moment, giving

$$\frac{dx}{dT} = s_e \frac{(S_e - x)}{S_e}. \qquad (2)$$

This differential equation may be integrated to yield

$$x = S_e - (S_e - x_0)e^{-qT}, \qquad (3)$$

where x_0 is the initial value of x, and q represents the ratio s_e/S_e. Thus x will increase from its initial value to approach the limiting value, S_e, in a negatively accelerated curve. A method of evaluating x in these equations from empirical measures of response latency, or reaction time, will be developed in a later section.

If the remainder of the situation has been experimentally neutralized, the probability of R in the presence of a sample from S_e will be given by the ratio x/S_e. Representing this ratio by the single letter p, and making appropriate substitutions in (3), we have the following expression for probability of R as a function of the number of reinforced trials.

$$p = 1 - (1 - p_0)e^{-qT}. \qquad (3')$$

Since we have not assumed any special properties for the original (or unconditioned) stimulus other than that of regularly evoking the response to be conditioned, it is to be expected that the equations developed in this section will describe the accumulation of conditional relations in other situations than classical conditioning, provided that other experimental operations function to ensure that the response to be learned will occur in the presence of every sample drawn from the S-population.

OPERANT CONDITIONING: REINFORCEMENT BY CONTINGENT STIMULATION

In the more common type of experimental arrangement, various termed operant, instrumental, trial and error, etc. by different investigators, the response to be learned is not elicited by a controlled original stimulus, but has some initial strength in the experimental

situation and occurs originally as part of so-called "random activity." Here the response cannot be evoked concurrently with the presentation of each new stimulus sample, but some of the same effects can be secured by making changes in the stimulating situation contingent upon occurrences of the response. Let us consider a situation of this sort, assuming that the activities of the organism have been catalogued and classified into two categories, all movement sequences characterized by a certain set of properties being assigned to class R and all others to the class R_e, and that members of class R are to be learned.

If changes in the stimulus sample are independent of the organism's behavior, we should expect instances of the two response classes to occur, on the average, at rates proportional to their initial probabilities. For if x elements from the S-population are originally conditioned to R, then the probability of R will be x/S; the number of new elements conditioned to R if an instance occurs will be $s[(S-x)/S]$, s again representing the number of stimulus elements in a sample; and the mathematically expected increase in x will be the product of these quantities, $sx[(S-x)/S^2]$. At the same time, the probability of R_e will be $(S-x)/S$, and the number of new elements conditioned to R_e if an instance occurs will be sx/S; multiplying these quantities, we have $sx[(S-x)/S^2]$ as the mathematically expected decrease in x. Thus we should predict no average change in x under these conditions.

In the acquisition phase of a learning experiment two important restrictions imposed by the experimenter tend to force a correlation between changes in the stimulus sample and occurrences of R. The organism is usually introduced into the experimental situation at the beginning of a trial, and the trial lasts until the pre-designated response, R, occurs. For example, in a common discrimination apparatus the animal is placed on a jumping stand at the beginning of each trial and the trial continues until the animal leaves the stand; a trial in a runway experiment lasts until the animal reaches the end box, and so on. Typically the stimulating situation present at the beginning of a trial is radically changed, if not completely terminated, by the occurrence of the response in question; and a new trial begins under the same conditions, except for sampling variations, after some pre-designated interval. The pattern of movement-produced stimuli present during a trial may be changed after occurrences of R by the evocation of some uniform bit of behavior such as eating or drinking; in some cases the behavior utilized for this purpose must be established by special training prior to a learning experiment. In the Skinner box, for example, the animal is trained to respond to the sound of the magazine by approaching it and eating or drinking. Then when operation of the magazine follows the occurrence of a bar-pressing response during conditioning of the latter, the animal's response to the magazine will remove it from the stimuli in the vicinity of the bar and ensure that for an interval of time thereafter the animal will not be exposed to most of the S-population; therefore the sample of elements to which the animal will next respond may be considered very nearly a new random sample from S.

In the simplest operant conditioning experiments it may be possible to change almost the entire stimulus sample after each occurrence of R (complete reinforcement), while in other cases the sampling of only some restricted portion of the S-population is correlated with R (partial reinforcement). We shall consider the former

case in some detail in the remainder of this section.

By our definition of the conditional relation, we shall expect all R-classes from which instances actually occur on any trial to be conditioned to stimulus elements present on that trial. The first movement to occur will be conditioned to the environmental cues present at the beginning of the trial; the next movement will be conditioned to some external cues, if the situation is not completely constant during a trial, and to proprioceptive cues from the first movement, and so on, until the predesignated response, R, occurs and terminates the trial. If complete constancy of the stimulating situation could be maintained, the most probable course of events on the next trial would be the recurrence of the same sequence of movements. In practice, however, the sample of effective stimulus elements will change somewhat in composition, and some responses which occur on one trial may fail to occur on the next. The only response which may never be omitted is R, since the trial continues until R occurs. This argument has been developed in greater detail by Guthrie (4). In order to verify the line of reasoning involved, we need now to set these ideas down in mathematical form and investigate the possibility of deriving functions which will describe empirical curves of learning.

Since each trial lasts until R occurs, we need an expression for the probable duration of a trial in terms of the strength of R. Suppose that we have categorized all movement sequences which are to be counted as "responses" in a given situation, and that the minimum time needed for completion of a response-occurrence is, on the average, h. For convenience in the following development, we shall assume that the mean duration of instances of class R is approximately equal to that of class R_e. Let the total number of stimulus elements available in the experimental situation be represented by S, the sample effective on any one trial by s, and the ratio s/S by q. The probability, p, of class R at the beginning of any trial will have the value x/S; if this value varies little within a trial, we can readily compute the probable number of responses (of all classes) that will occur before the trial is terminated. The probability that an instance of R will be the first response to occur on the trial in question is p; the probability that it will be the second is $p\ (1-p)$; the probability that it will be the third is $p(1-p)^2$; etc. If we imagine an indefinitely large number of trials run under identical conditions, and represent the number of response occurrences on any trial by n, we may weight each possible value of n by its probability (*i.e.*, expected relative frequency) and obtain a mean expected value of n. In symbolic notation we have

$$\bar{n} = \Sigma np(1-p)^{n-1} = p\Sigma n(1-p)^{n-1}.$$

The expression inside the summation sign will be recognized as the general term of a well-known infinite series with the sum $1/(1-(1-p))^2$. Then we have, by substitution,

$$\bar{n} = p/(1-(1-p))^2 = 1/p.$$

Then $\bar{L}$, the average time per trial, will be the product of the expected number of responses and the mean time per response.

$$\bar{L} = \bar{n}h = h/p = Sh/x.$$

Since R will be conditioned to all new stimulus elements present on each trial, we may substitute for x its equivalent from equation (3), dropping the sub-

scripts from S_c and s_c, and obtaining

$$\bar{L} = \frac{Sh}{S - (S - x_0)e^{-qT}} = \frac{h}{1 - \frac{(\bar{L}_0 - h)e^{-qT}}{\bar{L}_0}}. \quad (4)$$

Thus, $\bar{L}$ will decline from an initial value of $\bar{L}_0$ (equal to Sh/x_0) and approach the asymptotic minimum value h over a series of trials.

A preliminary test of the validity of this development may be obtained by applying equation (4) to learning data from a runway experiment in which the conditions assumed in the derivation are realized to a fair degree of approximation. In Fig. 1 we have plotted acquisition data reported by Graham and Gagné (3). Each empirical point represents the geometric mean latency for a group of 21 rats which were reinforced with food for traversing a simple elevated runway. The theoretical curve in the figure represents the equation

$$\bar{L} = \frac{2.5}{1 - .9648e^{-.12T}},$$

where values of $\bar{L}_0$, h, and q have been estimated from the data. This curve appears to give a satisfactory graduation of the obtained points and, it might be noted, is very similar in form to the theoretical acquisition curve developed by Graham and Gagné. The present formulation differs from theirs chiefly in including the time of the first response as an integral part of the learning process. The quantitative description of extinction in this situation will be presented in a forthcoming paper.

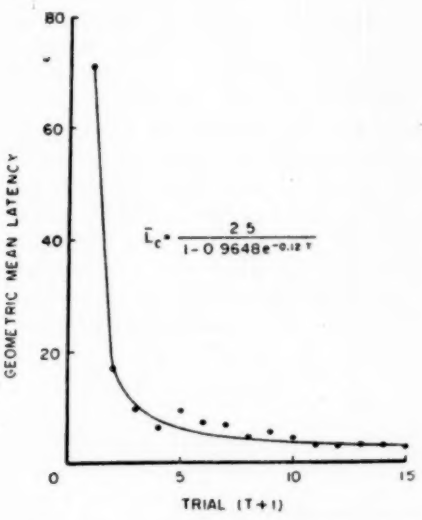

FIG. 1. Latencies of a runway response during conditioning, obtained from published data of Graham and Gagné (3), are fitted by a theoretical curve derived in the text.

In order to apply the present theory to experimental situations such as the Skinner box, in which the learning period is not divided into discrete trials, we shall have to assume that the intervals between reinforcements in those situations may be treated as "trials" for analytical purposes. Making this assumption, we may derive an expression for rate of change of conditioned response strength as a function of time in the experimental situation, during a period in which all responses of class R are reinforced.

$\bar{L}$, as defined above, will represent the time between any two occurrences of R. Then if we let t represent time elapsed from the beginning of the learning period to a given occurrence of R, and T the number of occurrences (and therefore reinforcements) of R, we have from the preceding development

$$\bar{L} = Sh/x.$$

Since $\bar{L}$ may be considered as the increment in time during a trial, we can write the identity

$$\frac{\Delta x}{\Delta t} = \frac{\Delta x}{\Delta T} \cdot \frac{\Delta T}{\Delta t}.$$

Substituting for $\Delta x/\Delta T$ its equivalent from (1), without subscripts, and for

$\Delta T/\Delta t$ its equivalent from the preceding equation, we have

$$\frac{\Delta x}{\Delta t} = \frac{s(S-x)}{S} \cdot \frac{x}{hS} = \frac{s(S-x)x}{hS^2}. \quad (5)$$

If the change in x per reinforcement is small and the process is assumed continuous, the right hand portion of equation (5) may be taken as the value of the derivative dx/dt and integrated with respect to time—

$$x = \frac{S}{1 + \frac{(S-x_0)}{x_0} e^{-Bt}}, \quad (6)$$

where $B = s/Sh$. In general, this equation defines a logistic curve with the amount of initial acceleration depending upon the value of x_0. Curves of probability (x/S) *vs.* time for $S = 100$, $B = 0.25$, and several different values of x_0 are illustrated in Fig. 2.

Since we are considering a situation in which a reinforcement is administered (or a new "trial" is begun) after each occurrence of R, we are now in a position to express the expected rate of occurrence of R as a function of time. Representing rate of occurrence of R by $r = dR/dt$, and the ratio $1/h$ by w, we have

$$r = \frac{dR}{dt} = \frac{dT}{dt} = \frac{wx}{S} = \frac{w}{1 + \frac{(S-x_0)}{x_0} e^{-Bt}}$$

and if we take the rate of R at the beginning of the experimental period as $r_0 = wx_0/S$ this relation becomes

$$r = \frac{w}{1 + \frac{(w-r_0)}{r_0} e^{-Bt}}. \quad (7)$$

To illustrate this function, we have plotted in Fig. 3 measures of rate of

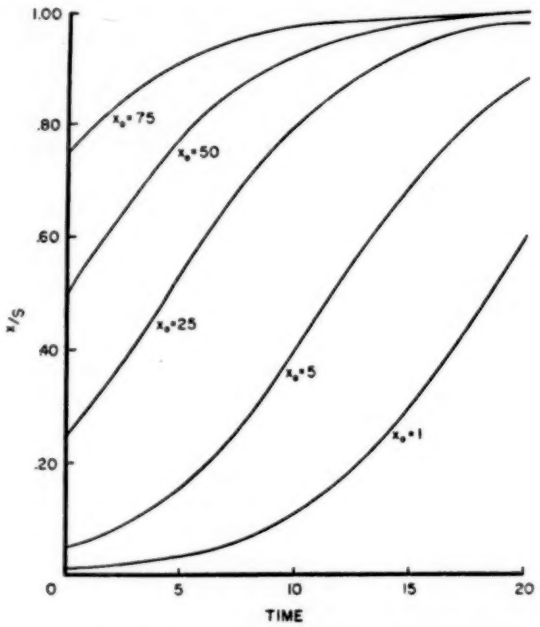

FIG. 2. Illustrative curves of probability *vs.* time during conditioning; parameters of the curves are the same except for the initial x-values.

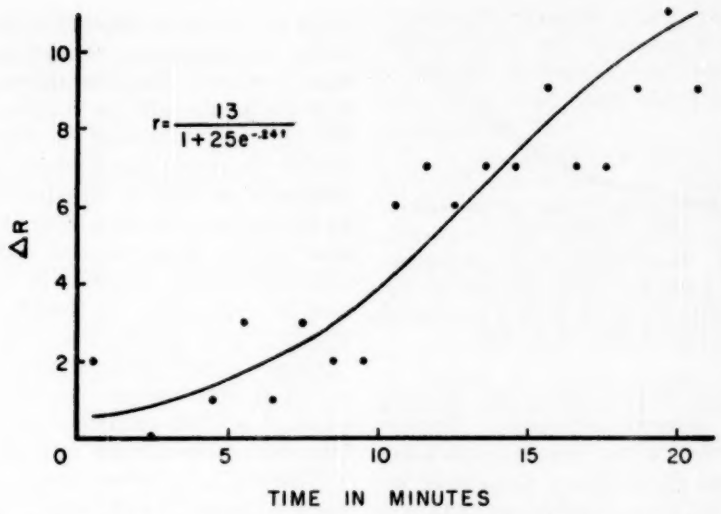

FIG. 3. Number of responses per minute during conditioning of a bar-pressing habit in a single rat; the theoretical curve is derived in the text.

responding during conditioning of a bar-pressing response by a single rat. The apparatus was a Skinner box; motivation was 24 hours thirst; the animal had previously been trained to drink out of the magazine, and during the period illustrated was reinforced with water for all bar-pressing responses. Measures of rate at various times were obtained by counting the number of responses made during the half-minute before and the half-minute after the point being considered, and taking that value as an estimate of the rate in terms of responses per minute at the midpoint. The theoretical curve in the figure represents the equation

$$r = \frac{13}{1 + 25e^{-.24t}}.$$

A considerable part of the variability of the empirical points in the figure is due to the inaccuracy of the method of estimating rates. In order to avoid this loss of precision, the writer has adopted the practice of using cumulative curves of responses *vs.* time for most purposes, and fitting the cumulative records with the integral of equation (7):

$$R = wt + \frac{w}{B}\log\left(\frac{r_0}{w} + \frac{(w - r_0)}{w}e^{-Bt}\right), \quad (8)$$

where R represents the number of responses made after any interval of time, t, from the beginning of the learning period. The original record of responses *vs.* time, from which the data of Fig. 3 were obtained, is reproduced in Fig. 4. Integration of the rate equation for this animal yields

$$R = 13t + 125\log_{10}(.038 + .962e^{-.24t}).$$

Magnitudes of R computed from this equation for several values of t have been plotted in Fig. 4 to indicate the goodness of fit; the theoretical curve has not been drawn in the figure since it would completely obscure most of the empirical record. In an experimental report now in press (2), equation (8) is fitted to several mean conditioning curves for groups of four rats; in all cases, the theoretical curve accounts for

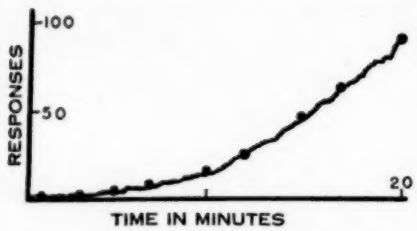

FIG. 4. Reproduction of the original cumulative record from which the points of Fig. 3 were obtained. Solid circles are computed from an equation given in the text.

more than 99 per cent of the variance of the observed R values. Further verification of the present formulation has been derived from that study by comparing the acquisition curves of successively learned bar-pressing habits, obtained in a Skinner-type conditioning apparatus which included two bars differing only in position. It has been found that the parameters w and s/S can be evaluated from the conditioning curve of one bar response, and then used to predict the detailed course of conditioning of a second learned response.

The overall accuracy of these equations in describing the rate of conditioning of bar-pressing and runway responses should not be allowed to obscure the fact that a small but systematic error is present in the initial portion of most of the curves. It is believed that these disparities are due to the fact that experimental conditions do not usually fully realize the assumption that only one R-class receives any reinforcement during the learning period. A more general formulation of the theory, which does not require this assumption, will be discussed in the next section.

PARTIAL REINFORCEMENT

It can be shown that a given response may be "learned" in a trial and error situation provided that some sub-population of stimulus elements is so controlled by experimental conditions that each sample of elements drawn from it is contiguous with an occurrence of the response. The sort of derivation needed to handle this kind of partial reinforcement will be sketched briefly in this section. A more detailed treatment will be given, together with relevant experimental evidence, in a paper now in preparation. It should be emphasized that we are using the term "partial" to refer to incomplete change of the stimulus sample on each occurrence of a given response, and not to periodic, or intermittent reinforcement.

Consider a behavior system involving two classes of competing behaviors, R and R_e, which may occur in a situation, S, composed of two independently manipulable sub-populations, S_r and S_e. Experimental conditions are to ensure that of the sample, s, of elements stimulating the organism at any time, elements from S_r remain effective until terminated by the occurrence of R, while elements from S_e remain effective until terminated by the occurrence of R_e. This kind of system might be illustrated by a Skinner box in which the entire stimulus sample is not terminated by occurrence of the bar-pressing response; for example, if the box is illuminated, the visual stimulation will be relatively unaffected by bar-pressing but will be terminated if the animal closes its eyes (the latter behavior being, then, an instance of R_e).

Let x represent the total number of elements from S conditioned to R at a given time, x_r the number of elements from S_r conditioned to R, T_r and T_e the numbers of occurrences of R and R_e prior to the time in question, and q the ratio s/S. By reasoning similar to that utilized in deriving equations (2) and (5), we may obtain for the average rate of change of x_r with respect to

T_r at any time

$$\frac{dx_r}{dT_r} = s \cdot \frac{S_r}{S} \cdot \frac{(S_r - x_r)}{S_r} = q(S_r - x_r). \quad (9)$$

This may be integrated to yield

$$x_r = S_r - (S_r - x_{r0})e^{-qT_r}, \quad (10)$$

which is identical in form with equation (2).

The other component of x, $(x - x_r)$, will decrease as these elements become conditioned to the competing response class, R_e, according to the following relations.

$$\frac{d(x - x_r)}{dT_e} = \frac{-s(S - S_r)}{S} \cdot \frac{(x - x_r)}{(S - S_r)} = -q(x - x_r) \quad (11)$$

and the integral,

$$x - x_r = (x_0 - x_{r0})e^{-qT_e}. \quad (12)$$

It will be observed that an analogous set of equations could be written for changes in the number of elements conditioned to R_e, and that the argument could be extended to any number of mutually exclusive classes of responses. From these relations it is not difficult to deduce differential equations which may be at least numerically integrated to yield curves giving probability of occurrence of each response class as a function of number of reinforcements. We shall not carry out the derivations here, but shall point out a number of properties of the curves obtained which will be evident from inspection of equations (10) and (12).

1. Regardless of the initial probabilities, the behavior system will tend to a state of equilibrium in which the final mean probability of R will be S_r/S and the final mean probability of R_e will be $(S - S_r)/S$.

2. If the number of elements from S conditioned to R at the start of an experiment is greater than S_r, the probability of R will decrease until the equilibrium is reached. (Of course all statements made here about R have analogues for R_e.)

3. If the number of elements from S conditioned to R at the start of an experiment is less than S_r, the probability of R will increase until the equilibrium value is reached.

4. If all elements originally conditioned to R belong to the sub-population S_r, then the curve relating probability to number of reinforcements will be identical with equation (3′) except for the asymptote, which will be S_r/S rather than unity.

5. If some of the elements originally conditioned to R do not belong to S_r, but x_0 is less than S_r, then the curve relating probability to number of reinforcements will rise less steeply at first than equation (3′), and may even have an initial positively accelerated limb.

It will be noted that from the present point of view, conditioning and extinction are regarded simply as two aspects of a single process. In practice we categorize a given experiment as a study of conditioning or a study of extinction depending upon which behaviors are being recorded. It seems quite possible that both conditioning and extinction always occur concurrently in any behavior system, and that the common practice of regarding them as separate processes is based more on tradition and the limitations of recording apparatus than upon rational considerations. In the present formulation, reinforcement is treated as a quantitatively graded variable with "pure extinction" at one end of a continuum. Any portion of an S-population may be related to an R-class by experimental conditions which produce a correlation between stimulus sampling and R-occurrences. Under given conditions of reinforcement an R-class may in-

crease or decrease in probability of occurrence over a series of trials depending upon whether the momentary probability is less than or greater than the equilibrium value for those conditions.

DISCUSSION

The foregoing sections will suffice to illustrate the manner in which problems of learning may be handled within the framework of a statistical theory. The extent to which the formal system developed here may be fruitfully applied to interpret experimental phenomena can only be answered by a considerable program of research. A study of concurrent conditioning and extinction of simple skeletal responses which realizes quite closely the simplified conditions assumed in the derivations of the present paper has been completed, and a report is now in press. Other papers in preparation will apply this formulation to extinction, spontaneous recovery, discrimination, and related phenomena.

The relation of this program to contemporary theories of learning requires little comment. No attempt has been made to present a "new" theory. It is the purpose of our investigation to clarify some of the conceptions of learning and discrimination by stating important concepts in quantitative form and investigating their interrelationships by mathematical analysis. Many similarities will be noted between functions developed here and "homologous" expressions in the quantitative formulations of Graham and Gagné (3) and of Hull (6). A thorough study of those theories has influenced the writer's thinking in many respects. Rather than build directly on either of those formulations, I have felt it desirable to explore an alternative point of view based on a statistical definition of environment and behavior and doing greater justice to the theoretical views of Skinner and Guthrie. A statistical theory seems to be an inevitable development at the present stage of the science of behavior; agreement on this point may be found among writers of otherwise widely diverse viewpoints, *e.g.*, Brunswik (1), Hoagland (5), Skinner (7), and Wiener (9). It is to be expected that with increasing rigor of definition and continued interplay between theory and experiment, the various formulations of learning will tend to converge upon a common set of concepts.

It may be helpful to outline briefly the point of view on certain controversial issues implied by the present analysis.

Stimulus-response terminology. An attempt has been made to overcome some of the rigidity and oversimplification of traditional stimulus-response theory without abandoning its principal advantages. We have adopted a definition of stimulus and response similar to Skinner's (7) concept of generic classes, and have given it a statistical interpretation. Laws of learning developed within this framework refer to behavior systems (as defined in the introductory section of this paper) rather than to relations between isolated stimulus-response correlations.

The learning curve. This investigation is not intended to be another search for "the learning function." The writer does not believe that any simple function will be found to account for learning independently of particular experimental conditions. On the other hand, it does seem quite possible that from a relatively small set of definitions and assumptions we may be able to derive expressions describing learning under various specific experimental arrangements.

Measures of behavior. Likelihood of responding has been taken as the primary dependent variable. Analyses presented above indicate that simple rela-

tions can be derived between probability and such common experimentally obtained measures as rate of responding and latency.

Laws of contiguity and effect. Available experimental evidence on simple learning has seemed to the writer to require the assumption that temporal contiguity of stimuli and behavior is a necessary condition for the formation of conditional relations. At the level of differential analysis, that is of laws relating momentary changes in behavior to changes in independent variables, no other assumption has proved necessary at the present stage of the investigation. In order to account for the accumulation of conditional relations in favor of one R-class at the expense of others in any situation, we have appealed to a group of experimental operations which are usually subsumed under the term "reinforcement" in current experimental literature. Both Guthrie's (4) verbal analyses and the writer's mathematical investigations indicate that an essential property of reinforcement is that it ensures that successive occurrences of a given R will be contiguous with different samples from the available population of stimuli. We have made no assumptions concerning the role of special properties of certain after-effects of responses, such as drive-reduction, changes in affective tone, etc. Thus the quantitative relations developed here may prove useful to investigators of learning phenomena regardless of the investigators' beliefs as to the nature of underlying processes.

SUMMARY

An attempt has been made to clarify some issues in current learning theory by giving a statistical interpretation to the concepts of stimulus and response and by deriving quantitative laws that govern simple behavior systems. Dependent variables, in this formulation, are classes of behavior samples with common quantitative properties; independent variables are statistical distributions of environmental events. Laws of the theory state probability relations between momentary changes in behavioral and environmental variables.

From this point of view it has been possible to derive simple relations between probability of response and several commonly used measures of learning, and to develop mathematical expressions describing learning in both classical conditioning and instrumental learning situations under simplified conditions.

No effort has been made to defend the assumptions underlying this formulation by verbal analyses of what "really" happens inside the organism or similar arguments. It is proposed that the theory be evaluated solely by its fruitfulness in generating quantitative functions relating various phenomena of learning and discrimination.

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BEHAVIOR, PERCEPTION AND THE PSYCHOPHYSICAL METHODS [1]

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In a forthcoming review (Graham, 10), it is stated that the "psychophysical" methods constitute one of the most fruitful ways of obtaining data that, formulated in stimulus-response terms, may provide the ensemble of quantitative relations necessary to define and explain the field of visual perception. When procedures other than psychophysical methods are used, and in particular, when responses are not properly restricted by "instruction stimuli," the data obtained are in terms of "introspective" reports that are neither easily interpretable quantitatively nor classifiable at a level higher than social conversation.

The observable variables of the psychophysical experiment are responses on the one hand, and stimulus operations on the other. The stimulus-response function represented by a given psychophysical curve describes how differential, restricted responses correlate with such stimulus operations as the presentation of systematically varied objects, words, and energies. Such data, it is asserted, are discrimination data.

The validity of the position represented by these statements may or may not be obvious. In any case the data of the psychophysical experiment involve, at various levels of analysis, considerable degrees of complexity, and further supporting discussion may be desirable. The present account is concerned, then, with a consideration of the stimulus operations and responses encountered in the various types of psychophysical experiment. A later part of the discussion will consider some theoretical aspects of the ensemble of relations that specifies the field of visual perception.

[1] This account was prepared under Project NR 142–404; Contract N6onr-271, Task Order IX, between Columbia University and the Office of Naval Research, U. S. Navy. Reproduction in whole or in part permitted for any purpose of the United States Government.

General

The history of the psychophysical methods (Titchener, **35**; Boring, **4**) is a history of the development of a methodology for specifying relations between stimuli and what, in the opinions of different workers, were, variously: sensation (Fechner, **6**, pp. 1–12), sense distance (Titchener, **34**, pp. xxi–xxvii; **35**, pp. cxvi–cxliv), error (Fullerton and Cattell, **8**, pp. 23–26), and response (Johnson, **22**, **23**; Graham, **9**; Bergmann and Spence, **3**). In the writer's opinion the presumed variables of sensation, sense distance and error have little meaning except in terms of a response definition or reference, and the long controversial history of the problem seems to bear out this conclusion by high-lighting inconsistencies that developed in the absence of response specification.

Elaborate quantitative procedures have been worked out for the stimulus-response relations of the psychophysical experiment. The literature on this topic is voluminous, and the reader is referred to Titchener (**35**), Woodworth (**39**, chapters 17 and 18), Guilford (**14**) and Johannsen (**21**) for extended treatments.

An operational description of a psychophysical experiment requires a statement of an instruction stimulus, and very often such a statement is sufficient

to provide reliable data. Nevertheless, the advancement of psychological science requires not only that the instruction stimulus be stated but that its effects be understood. The instruction stimulus may be thought of as the "selector" of a given class of discriminations, and it is an important parameter of any relation existing between responses and their associated aspects of stimuli. The stimulus-response formulae resulting from psychophysical experiments must remain incomplete so long as appropriate instruction-stimulus parameters remain unanalyzed and incompletely specified (as, *e.g.*, at the level of restating an original wording).

A stimulus may be defined as some energy function that is correlated with a response. The particular energy function specific to a given stimulus-response relation depends upon a great many circumstances. In certain cases, for example, in the matter of visual threshold, the relevant energy function is intensity, a variable that may be specified within the theoretical system provided by physics. In other cases, the energy functions are not fruitfully described in physical terms; when response is not an easily expressible function of a physical aspect of a stimulus but seems to depend simply on the presence or absence of a given class of events, some other method of classification may be proper. For example, it may be more immediately fruitful to consider the energy functions as words, objects, etc.

Consider an example in the field of aesthetics. One may order a group of pictures according to the frequencies of occurrence of the responses "Pleasant" and "Unpleasant"; and in fact the presentation of each picture may be considered to be a stimulating operation that relates to a response quantified according to its frequency of occurrence. However, it must be observed that the quantified response is not an easily recognizable function of a quantified aspect of stimulus. In fact, the present basis for classifying such stimuli is in terms of the responses that they elicit (*i.e.*, the pictures are classified as "pleasant" or "unpleasant"). Experiments of this sort are usually of the type that is concerned with the question of reproducibility of response quantities within a population of subjects. The method of paired comparison (Guilford, 14), which will not be discussed here, is most appropriate for such investigations. Obviously in this type of work it is of first importance to conduct a program on the nature of the effects produced by the stimulus operations and their interaction with "conditions" of the organism determined by instruction. The program, of course, may result in analysis different from that traditional to the field of perception, but there is no reason for restricting one's efforts to traditional paths when an answer to a problem is at issue.

In the descriptions that follow, emphasis will be placed on applications of the psychophysical methods to experiments in which the stimulus variable is not classified on a response basis. In addition, we shall pay attention to situations that make use of a maximum of response restriction, *i.e.*, that allow for a minimum of response categories. For example, the treatment of the method of constant stimuli with more than two response categories is not considered.

THE METHOD OF CONSTANT STIMULI

The experiment on the determination of visual threshold may be used as an example of the application of this method. The dark adapted subject is instructed to maintain regard on a fixation light and to report "Yes" if, after a signal, he discriminates another light in the field, and "No" if he does not. The method involves a determination

of how the frequency of occurrence of one of the two permissible, contrasting responses (the "Yes" response) varies with changes in the intensity of stimulus light. Thus, for visual threshold, one may plot the percentage of occurrence (P_p) of the positive response "Yes" against some function of the intensity (*e.g.*, the logarithm) over a small range of intensities. Above the critical range the response occurs 100 per cent of the time, and below the range the response occurs at a zero (or "chance guessing") level. When two categories of response are used, the percentage of occurrence of the negative response ("No") is simply $100 - P_p$, where P_p is the percentage of occurrence of the positive response.

In this type of experiment one wishes to know the value of the stimulus intensity function that corresponds to a given percentage of occurrence of the positive response, *i.e.*, the threshold. The particular percentage chosen may be arbitrary, but it will probably be determined by the statistical hypothesis that is being tested. For example, the mean threshold stimulus value calculated on the basis of a Gaussian distribution is determined at the 50 per cent point of the cumulative function, whereas the per cent point for the mean stimulus value for a Poisson distribution (Fry, 7) varies with other parameters of the function (*e.g.*, the second moment) and approaches 50 only as a limiting value. In either case theoretical assumptions are made with respect to the relationship between stimulus and response, and the experimental data provide a test of theory (Mueller, 27).

The constant stimulus method may be extended to the intensity discrimination experiment. A common form of this experiment presents the subject with a field illuminated by an intensity I. The subject becomes light adapted to this intensity and is instructed to report "Yes" if, after a signal, he discriminates a momentary brightening of the field (provided by a variable, momentarily added intensity, ΔI). If he does not discriminate a momentary brightening, he is to report "No." Frequencies of occurrence of "Yes" are plotted as a function, for example, of log ΔI, and the threshold is determined as previously. (A curve in which the frequency of occurrence of "Yes" responses is plotted against an appropriate intensity variable is sometimes called a "frequency of seeing" curve.) An hypothesis as to the form of the frequency distribution will determine the threshold, and indeed, it may also test an hypothesis as to photochemical (Hecht, Shlaer and Pirenne, 19) or behavior activity. When the experiment is repeated at various values of I, a series of threshold ΔI values is obtained, and on this basis one may plot an intensity discrimination curve.

Figure 1 gives frequency of seeing curves as functions of log ΔI at several levels of adapting intensity, I. The data are for subject R in Mueller's experiment (28). A frequency of seeing curve was obtained twice at each value of I, and the I value at which each curve was determined is given as a numerical label for each associated pair of curves.

At a low value of I, the frequency of seeing curve occurs at low values of log ΔI; at a high value of I, the frequency of seeing curve is displaced to high values of log ΔI. The curves assume intermediate positions for intermediate values of I. Each curve presents a typical sigmoid appearance. The threshold value of ΔI, *i.e.*, ΔI_t, may be determined for each curve as the ΔI value that occurs at a 50 percent frequency of seeing (or some other fiducial percentage determined on an appropriate theoretical basis).

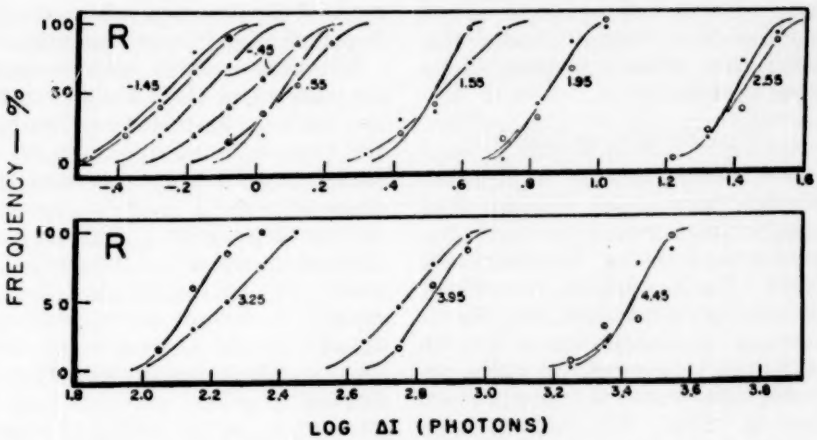

FIG. 1. Frequency of seeing curves for subject *R* in Mueller's experiment (28). The number associated with each pair of curves is log *I* in photons. Data were obtained by the method of constant stimuli.

The log ΔI_t values as determined in the manner described may be used to provide an intensity discrimination curve. When each ΔI_t value is divided by its corresponding adapting intensity value, *I*, the Fechner ratio is given. This ratio, or some function of it, *e.g.*, its log, dictated by appropriate theoretical considerations, may be plotted against log *I* to give an intensity discrimination curve. Such a curve is presented in Fig. 2. This curve shows that log $(\Delta I_t/I)$ is high at low values of *I* and decreases to a final limiting value at a high intensity.

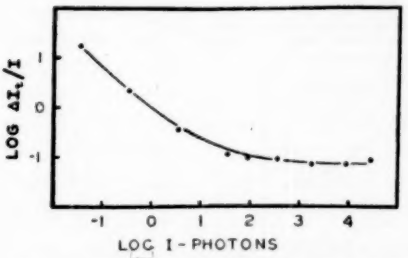

FIG. 2. The intensity discrimination curve obtained by Mueller (28). ΔI_t values are determined at the fifty per cent frequency of seeing value for each curve in Fig. 1. Log $(\Delta I_t/I)$ is then computed and plotted against log *I*. $\Delta I_t/I$ is high for low intensities and decreases to a final limiting value at high intensities. The curve drawn through the data is the curve of equation (8) which represents Hecht's theory (17) of intensity discrimination.

THE METHOD OF SINGLE STIMULI

In using this method (Wever and Zener, 38; Volkmann, 37) the experimenter instructs the subject to respond in terms of a set number of categories to a single stimulus that may be varied in a given dimension. The simplest situation requires only two response categories, and under this condition the method is identical with the method of constant stimuli as used in the determination of absolute thresholds. (See, for example, the experiment of Veniar [36] on difference thresholds for shape distortion of geometrical squares.)

When three response categories are used, the method is comparable to the method of constant stimuli applied to the absolute threshold with an "Uncertain" category.

It is only when more than three response categories are used that the method differs from the conventional constant method. Under such circum-

stances the method of single stimuli may become a "rating" method that entails some difficult problems of response specification.

THE METHOD OF LIMITS

This method employs a procedure whereby the stimulus variable under consideration is varied in small consecutive steps until a response change occurs. For example, in determining the absolute visual threshold, the intensity of the stimulus area is varied in small steps of increasing intensity, until the subject's response changes from "No" to "Yes." The intensity value (or, for example, its logarithm) used in computing the threshold is taken as a value interpolated between the value corresponding to the last negative response ("No") and that corresponding to the first positive response ("Yes"). The order of presentation of intensity is reversed for the second determination of the threshold datum, and the final threshold is determined as an average of all the data obtained in a number of ascending and descending orders.

The method may be used for obtaining many types of threshold, including the intensity discrimination threshold. For example, in an experiment on the latter, the subject, light adapted to a given intensity, I, may be instructed to respond positively ("Yes") to a discriminated momentary increase in intensity, ΔI, and negatively ("No") to no change. The ΔI values corresponding to a change in response are found for successive series (in ascending and descending orders) and their frequencies may be plotted against ΔI or some function of ΔI (for example, log ΔI). The threshold value of the ΔI function is determined as an average of the distribution.

Figure 3A gives a distribution of ΔI values (each corresponding to a change in response) for a single subject at an adapting intensity, I, of 28,300 photons. This value of I is identical with the highest intensity of Fig. 1, and the ΔI_t

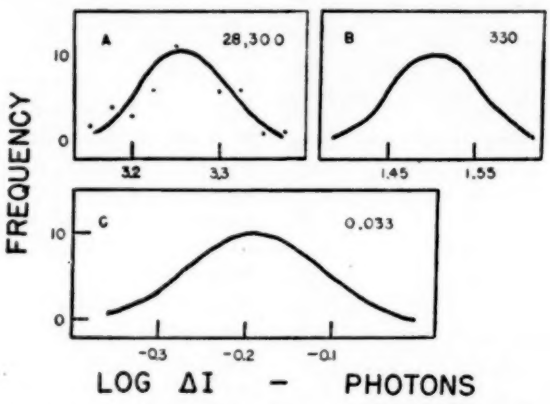

FIG. 3. Curves giving distributions of ΔI values (each corresponding to a change in response) for a single subject at three adapting intensities. Method of limits, ascending series only. *A*: Data obtained experimentally at an I value of 28,300 photons; this I value is comparable to the highest I value of Fig. 1. *B*: A distribution computed for 330 photons by the method described in the text. *C*: A distribution computed for 0.033 photon. The data of *A* were provided by Dr. C. G. Mueller.

values are obtained under similar conditions except for the method used: the present case employs the method of limits with ascending series only; the case of Fig. 1, the method of constant stimuli.

Figure 3B is a hypothetical distribution of ΔI's for an adapting intensity, I, of 330 photons. Figure 3C is a presumed distribution obtainable at 0.033 photon.[2] Each curve in Figs. 3B or 3C (or any other figure that might present a curve for an intervening value of I) provides an average value of log ΔI that is, by definition, a threshold value, *i.e.*, log ΔI_t. Such values of log ΔI_t at various values of I give, on the appropriate calculation, an intensity discrimination curve comparable to that of Fig. 2.

Similar considerations as to the place of hypothesis in fitting data apply to this method as apply to the method of constant stimuli.

THE METHOD OF ADJUSTMENT

In this method the subject is presented with a constant, standard stimulus and a variable stimulus. He is instructed to manipulate the variable stimulus until it "matches" (*i.e.*, with respect to a given attribute it is indiscriminable from) the standard stimulus (Woodworth, **39**, chapter 17). The average value of the stimulus variable resulting from many individual matchings (adjustments) is taken as the "equality" value. The difference between the value of the standard stimulus variable and the "equality" value gives the "constant error," a measure of "accuracy" of setting. The standard deviation of the stimulus values resulting from the adjustment responses gives an inverse measure of precision of setting.

It may be argued that any given adjustment involves a serialized set of discriminations involving different responses and changing stimuli. For example, it is conceivable that when the subject makes a matching adjustment by a "bracketing" procedure, he presents himself with a variable stimulus to which he makes implicit responses, analogous to the overt responses of the method of limits. If such is the case, the method of adjustment has much in common with the method of limits. Such a supposition is theoretical and calls for a specification of the response components of the adjustment. No data on the problem exist at present, and an answer can only be arrived at by observation of a subject in the psychophysical experiment.

As yet, then, the method does not provide a true measure of a discriminable difference since only one response category is used, *i.e.*, adjustment; therefore, no frequency of response or response change may be noted. However, classification of response may be accomplished arbitrarily by the following device. Responses that lead to stimulus settings lying within plus or minus one standard deviation (or any other appropriate statistical fiducial limit) of the mean of the settings may be classed in the category "Equal." Responses that give settings more than a standard deviation below the mean are classed in the category "Less." Responses that give settings more than a standard deviation above the mean are classed in the category "Greater." By this device, a so-called just discriminable difference (*i.e.*, the standard de-

[2] The curves of Figs. 3B and 3C have been drawn so that (a) the dispersion of each is proportional to the slope of the corresponding psychophysical function (*i.e.*, for a comparable adapting intensity, I) of Fig. 1, and (b) so that the average ΔI is in appropriate ratio (comparable to that given in Fig. 1 for a corresponding I) to the experimentally determined value for 28,300 photons. (Photons $= (10/\pi) \times$ pupil area in square millimeters $\times$ brightness in millilamberts.)

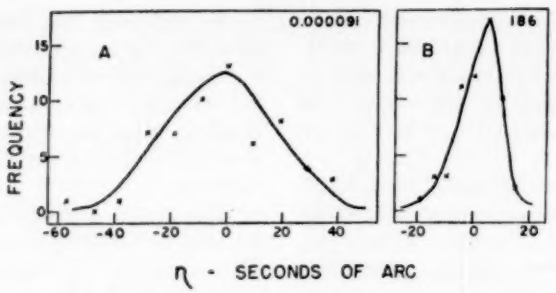

FIG. 4. Frequency distributions of stereoscopic settings computed in terms of η, in seconds of arc. *A*: A distribution of settings for an intensity of 0.000091 millilambert. *B*: A distribution for an intensity of 186 millilamberts. The data are for a single subject in the experiment by Mueller and Lloyd (29).

viation) may be obtained, but it is important to notice that the difference is not signalled by a true change in response, but rather by a classification of response on the basis of stimulus changes. All considerations of statistical "fits" of data that apply to the other methods apply to the method of adjustment.

Figure 4A presents data, obtained by the method of adjustment, for the determination of the least discriminable difference angle for stereoscopic vision, η_l.

The situation in which the observations were made involved t_ stereoscope with micrometer attachment described by Mueller and Lloyd (29). This stereoscope provides movement of a vertical line in the right-eye field, while the comparable line in the left-eye field remains stationary. These lines, when "fused," provide the comparison stimulus. The standard stimulus is provided by "fusion" of three short, vertical fiducial lines for each eye. Movement of the micrometer causes the vertical comparison line in the right-eye field to move horizontally in the frontal stereoscopic plane and thus causes the "apparent" spa .l position of the comparison stimulus to vary with respect to the standard stimuli.

On theoretical grounds (Graham, 10) it may be shown that a given setting of the micrometer corresponds to a difference in the convergence angles existing for the standard and comparison stimuli. This difference angle is called η; for a true "lining up" of standard and comparison stimuli its value is zero. Negative values of η mean a setting made nearer the subject than the true setting for "equality"; positive values, a setting farther from the subject than the true setting.

The distribution of η's for a low light intensity (0.000091 millilambert) is shown in Fig. 4A for Subject CGM of the Mueller and Lloyd (29) experiment. Figure 4B gives the distribution of settings for the same subject at the highest intensity used, 186 millilamberts. (In Mueller and Lloyd's experiment, from which these data come, distributions of η's were obtained at 8 intensities intervening between the two discussed here.) The threshold difference angle, η_l, is taken to be some measure of the variability of the η settings. In the present case the average deviation was used. η_l is the conventional inverse measure of stereoscopic acuity.

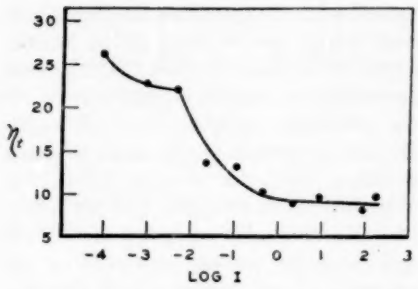

FIG. 5. The threshold, η_t, for stereoscopic vision, in seconds, as a function of field brightness in millilamberts. η_t is calculated for each value of intensity as the average deviation of a distribution similar to those given in Fig. 4A and 4B. The curve, the one obtained by Mueller and Lloyd (29), is the curve of equation (8) and represents Hecht's description (17). η_t is taken on theoretical grounds (29) to be equal to $\Delta I/I$.

When a threshold difference angle, η_t, is determined for 10 distributions of η (each distribution for a different intensity) and plotted against the logarithm of the prevailing intensity I, the graph of Fig. 5 is obtained. This graph shows the way in which η_t, a measure of stereoscopic acuity defined in terms of a geometrical theory of space perception, varies as a function of the prevailing intensity, I. η_t is high (*i.e.*, acuity is low) at low intensities and decreases as intensity increases, until, at high intensities, it reaches a final, low limiting value. The experimental values on the graph are averaged data for two subjects.

THE METHOD OF SENSE RATIOS

The methods of constant stimuli and limits may be used to signal absolute thresholds and just discriminable differences; the method of adjustment may be used to signal "equivalence" of stimuli, and by an arbitrary statistical device, a defined just discriminable difference. The method of ratios (Delboeuf, 5; Stevens and Volkmann, 33) has been used for the determination of a stimulus quantity that results from the instruction to adjust a stimulus so that it "bisects the interval" between two reference stimuli.

In the method of sense ratios the subject is presented with, for example, two illuminated patches, the patches differing in intensity of illumination (Merkel, 26). For any one experimental series the illumination of the patches is maintained constant at the given two levels. Between the two constant illuminated areas is another stimulus surface on which intensity of illumination is variable. The subject is instructed to respond "Yes" when he discriminates an intensity on the middle area as "halfway" between the intensities on the outer areas. His response to all other intensities is to be "No."

Within a small range of intensities the frequency of response "Yes" is distributed regularly, and the stimulus quantity for "bisection" may be determined as the average intensity value of the distribution. As to the meaning of the quantity: whether, for example, it represents a point on a stimulus continuum that corresponds to a signalling of *half* of something in the subject, that is a matter of theory. At any rate reproducible values are obtained; they have as parameters the intensities of the two comparison stimuli.

THE REACTION TIME METHOD

This method may be illustrated by a procedure followed by Steinman (31). The subject is light adapted to any one of a series of intensities, I. At any level of I, the subject is presented with various values of ΔI, and a determination of reaction time is made at each value of ΔI. By this procedure a curve may be obtained for reaction time as a function of ΔI at each value of I. The method gives a quantitative relation between stimulus and response, but, since

only one response (that varies in reaction time) is involved, we cannot obtain a just discriminable difference.

However, by the method of plotting reaction time against log ΔI for each value of log I, one gets a family of curves (one for each value of log I) that are parallel on the log ΔI parameter. This treatment was not used by Steinman, but recomputation of her data shows that it would probably be a true description if her log I range were increased by 1 to 2 log units and probably for ΔI durations of less than 0.03 second (Keller, 24). By cutting the curves at constant reaction times one may obtain, for a given reaction time, a value of ΔI, ΔI_c, for a given value of I. Depending on the reaction time chosen, one may then plot a conventional intensity discrimination curve in which log $(\Delta I_c/I)$ is plotted against log I, reaction time being the parameter that sets the ordinate position of each curve. Thus a certain stimulus value may be referred to some constant response in a manner comparable to that encountered in the constant stimulus method, when difference thresholds, each referable to the same constant response occurrence, are determined as functions of a given parameter (*e.g.*, adapting intensity, etc.).

The method has been used by Hecht (16) in experiments on *Mya;* experiments on human subjects have been few but promising (Woodworth, 39). Hartline (15), Graham and Riggs (12) and Graham and Hartline (11) have used a similar method with measures other than reaction time in experiments on electrical recording from the eyes of lower organisms.

SOME THEORY

An elaborate theoretical structure has arisen on the base provided by the psychophysical methods and has developed along the following lines. Fechner (6) started with the questionable generalization, based on Weber's lifted weight experiments, that the just discriminable increment in weight is proportional to the reference weight; *i.e.*, $\Delta W_t \propto W$. He then proposed, on the basis of other evidence, that the relation holds, not only for lifted weights, but for other just discriminable aspects of stimuli and for other sensory systems: *i.e.*, in general, $\Delta S_t \propto S$, where ΔS_t is the just discriminable increment in stimulus and S is the reference stimulus. Thus $\Delta S_t/S = C$, where C is a constant. The latter expression is called Weber's law, an empirical generalization that we now know to be invalid for large ranges of S.

Fechner carried the empirical approximation to a theoretical level by making the following assumption. Let ΔR, an hypothesized constant increment in sensation, be proportional to ΔS_t and inversely proportional to S. In these terms, $\Delta R \propto C(= \Delta S_t/S)$; and Weber's law is a measure of sensation by the concept that C is proportional to ΔR.

Suppose, now, that ΔR and ΔS_t may be considered so small (certainly ΔS_t is not) that they may be written as the differentials dR and dS. Then $dR = k\, dS/S$, where k is the constant of proportionality relating C and ΔR. On integration, we obtain the expression

$$R = k \log (S/S_0). \qquad (1)$$

Equation (1), which states a relation between R (sensation) and S (stimulus), is Fechner's law, in which S_0 is the threshold. For a treatment that has certain advantages over the present one, see Wright (40).

An interesting aspect of the testing of Fechner's law was concerned with experiments on the "bisection of sense distances." Consider two standard stimuli, S_1, the greater, and S_2, the smaller. A test stimulus, S_t, must be adjusted by the subject until it seems to be "half-way" between S_1 and S_2.

Now, by Fechner's law,

$$R_1 = k\,(\log S_1 - \log S_0), \quad (2)$$

$$R_2 = k\,(\log S_2 - \log S_0), \quad (3)$$

and

$$R_t = k\,(\log S_t - \log S_0). \quad (4)$$

On subtracting equation (4) from (2), we have

$$R_1 - R_t = k\,(\log S_1 - \log S_t); \quad (5)$$

and, similarly, on subtracting (3) from (4), we have

$$R_t - R_2 = k\,(\log S_t - \log S_2). \quad (6)$$

For bisection, $R_1 - R_t = R_t - R_2$; and we may set the right hand side of (5) equal to the right hand side of (6). The result is:

$$\log\,(S_1/S_t) = \log\,(S_t/S_2),$$

or

$$S_t = \sqrt{S_1 \cdot S_2}; \quad (7)$$

that is, the bisection threshold is the geometric mean of the two comparison stimuli. The agreement of data with prediction is not good, at least for vision (Titchener, **35**).

Recent criticisms serve to emphasize objections to Fechner's position that have been proposed at many stages of the history of psychophysics. For example, Johnson (**23**) points out some logical inconsistencies in the Fechnerian formulation. Johnson (**22**) and Graham (**9**) emphasize the problem of response in the psychophysical experiment and the kind of behavior functions that must be considered. Bergmann and Spence (**3**) show that scaling methods result in the scaling of stimuli. There is little need to go into all of the technical objections to Fechner's law, because of the primary fact that it fails at its very roots: $\Delta S_t/S$ is not constant; nor has it ever been seriously taken to describe the action of all stimulus aspects. (For example, it has never been considered to apply to hue discrimination.) Later experiments, particularly in vision, show the lack of constancy of $\Delta S_t/S$ plainly. In Fig. 2, if Fechner's law were true, log $(\Delta I_t/I)$ should be constant across the graph, and the curve would be a horizontal line. Of course it is not, and similar disagreements with theory have been shown by many experimenters since the days of König and Brodhun (**25**). Hecht (**17**) has predicted that the equation for visual intensity discrimination should be

$$\frac{\Delta I_t}{I} = c\left[1 + \frac{1}{(KI)^{\frac{1}{2}}}\right]^2, \quad (8)$$

where c and K are constants; ΔI_t, the discriminable increment in intensity; and I, the reference intensity. The equation does, in fact, fit intensity discrimination data (as it does in Fig. 2) when certain experimental conditions are fulfilled. The equation is derived, on theoretical grounds, from a consideration of photochemical processes in the eye. (See also K. E. Baker [**2**] for an analysis of the hypothesis in relation to vernier acuity and H. D. Baker [**1**] for an extension to light adaptation.)

SOME BROAD CONSIDERATIONS

It is probably true that psychological theory cannot be psychophysics on a grand scale, nor can one look for universal principles in psychophysical concepts. Rather, it seems that the application of psychophysical method is a first step in the setting up of conditions that allow for a scientific description of a stimulus-response relation. Properly conceived, it specifies variables. It also poses a relation between variables requiring explanation.

We may take it that the objective of a science of behavior is the explication of the relations implicit in the equation

$$R = f\,(a, b, c, d \ldots n \ldots t \ldots x, y, z). \quad (9)$$

In this equation, the first letters of the alphabet (a, b, c, etc.) refer to properly specified aspects of stimuli; the last letters (. . . x, y, z), to properly specified conditions of the organism; R, to response; n, to number of presentations; and t, to time. In what follows, the letters F, ϕ, f_1, and f_2 imply a functional relation between the left hand term of the particular equation referred to and the terms in parentheses.

Any psychophysical function may be described as a special case of (9); *i.e.*,

$$R = F(a), \qquad (10)$$

where all the variables of (9), except R and a, are constant. The effects of instruction stimuli are presumably specified by constant values of x, y, or z. A full specification of these latter terms may involve other cases of equation (9) that describe conditions due to verbal stimulation and their effects in time, t.

When an experiment requires the determination of several psychophysical functions to give a particular "perceptual" function, as in the case of intensity discrimination, we note how one aspect, b, of the stimulus situation (*e.g.*, the threshold increment in intensity, ΔI_t) varies as a function of another, a (*e.g.*, the adapting intensity, I). Thus, for constancy in all variables except a and b (but including R),

$$b = \phi(a). \qquad (11)$$

For the case where a discrimination depends upon a "condition," x, of the organism (*e.g.*, "emotion"),

$$R = f_1(x). \qquad (12)$$

Finally, in terms of equation (9), it is of some interest to observe that the case of learning reduces to

$$R = f_2(n), \qquad (13)$$

where n refers to number of presentations of the constant stimuli a, b, etc., and other variables assume constant parametric values. "Reinforcement" is presumably a specified value of x, y, or z traceable to the action of properly specified but constant stimulus variables (*i.e.*, the reinforcing agent).

It is readily enough seen that the precise specification of relations implied by equation (9) will require a program of research and theoretical analysis. Theories of sensory activity (Hecht, 18; Granit, 13; Stevens and Davis, 32), that tell something of initiating events and limiting conditions, will no doubt be important in describing important relations; and behavior theories (Hull, 20; Skinner, 30), that describe conditions of the organism, will be valuable. In any case, what must be attained is an explicit statement of the relations existing among stimulus, response, and whatever hypothesized variables, physiological and inferred, become logically necessary. The only criterion of the value of an hypothesized "condition" of the organism centers on the question: Does it play a fruitful rôle in a test of theory?

SUMMARY

1. Attention is given to some problems concerning stimulus and response in the psychophysical experiment. The rôle of instructions, classification of stimuli, and limitations of the subject's verbal response are discussed.

2. An examination is made of the stimulus-response relations of the following psychophysical methods: constant stimuli, single stimuli, limits, adjustment, sense ratios, and reaction time. Representative stimulus-response functions are described. It is concluded that the behavior evidenced in the psychophysical experiment is discrimination.

3. Some historical aspects of psychophysical theory are considered and criticized.

4. An attempt is made to relate the data of the psychophysical experiment

and perception to the field of behavior theory. It is shown in equation (10) that psychophysical functions are describable as special cases of the general behavior function of equation (9). In the special case a specifiable aspect of a stimulus is the essential variable, and terms representing number of presentations of stimuli, time, and specifiable conditions of the organism are constant.

In certain treatments that involve several psychophysical functions (*e.g.*, intensity discrimination), one variable aspect of the stimulus is treated in equation (11) as a function of another aspect of the stimulus, the response and all other variables remaining constant.

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DESCRIPTION OF THE LEARNED RESPONSE IN DISCRIMINATION BEHAVIOR

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The descriptive task of science is primarily one of abstraction or classification. Irrelevant differences are set aside to make possible a grouping of the data according to major significant identities or similarities. The decision as to what differences are significant and which ones may be disregarded as incidental has far-reaching consequences which delimit the theoretical structure into which the facts may be eventually organized. Any systematization, erected prematurely on inadequate classifications of the empirical data, will be wasteful. For psychology, which, as Northrop (9) points out, is still predominantly in the second or natural history stage of science, the proper selection of descriptive categories is of fundamental present-day importance.

Inclusion of all pertinent facts in a minimum number of classes has the obvious advantage of facilitating subsequent mathematical-theoretical manipulations (7, 14). Its danger lies in the necessary exclusion of distinctions which may be even more important than those on which the actually used divisions are based. In psychology, reduction in number of classes frequently has been carried to its penultimate extreme, as is exemplified by a variety of commonly used dichotomies: innate-acquired, subliminal-supraliminal, right-wrong, yes-no.

The particular concern of this paper is with two sets of terms extensively employed in reporting behavioral data from animal studies involving two-choice problem situations. They describe the response as turning right *versus* turning left or, alternatively, as approach *versus* avoidance. (These alternatives have been designated as "movements" or "motor patterns," and "cathexes" or "acts," by Tolman and Guthrie, respectively.) Usually both sets of terms are accepted, one or the other being applied according to the kind of situation under consideration (5, 13). Some writers use the two sets so indiscriminately, and even interchangeably, as to imply synonymy. This identification is erroneous and may have serious consequences. Even introspective evidence suggests a critical difference: "reaching towards the right" (when green happens to be at the right, red at the left), is not the same thing as "approaching (or reaching towards) green."

There are certain experiments in which differentiation is most conveniently described in terms of discrete muscular movements—movements whose only spatial reference is to the subject's own body. Such responses do not lend themselves readily to the approach-avoidance formulation. This would be the case, for instance, in an auditory discrimination in which the subject must make a left turn (or must press the telegraph key on the left) in response to one sound, and must make a right turn (press the right key) when a different sound is heard. On the other hand, the difficulties and inconsistencies inherent in the left-right formulation when applied to other instances of discrimination behavior, especially in the visual field, have not been fully recognized (although some writers have found it convenient to make general use of the approach-avoidance classifi-

cation). In the interest of simplification or economy, consequently, there has been a tendency to describe *all* two-choice discriminations as orientational (*e.g.*, left-right) responses. The following two instances will serve to illustrate this trend.

In 1938 Gulliksen and Wolfle (1) presented a provocative and mathematically precise "theory of learning and transfer." In this theory the response is defined "as being a jump to the right or a jump to the left, and the stimulus as consisting of the entire configuration presented on a given trial" (1, p. 244). It may be pointed out here 1) that there is no more *a priori* justification for this assumption than for the alternative one which defines the responses as approach to the positive and avoidance of the negative stimulus-object, and 2) that many of the predictions or deductions from a theory based on the second alternative would be quite different than those deriving from the Gulliksen and Wolfle formulation.

More recently several writers have proposed neural structures, analogous to mechanical devices, as offering an explanation for the workings of the central nervous system in guiding and regulating behavior. Thus Householder (3) presents a fairly simple structure for discrimination, a rather more complicated one for transposition. In both cases the neurophysiological postulates are few in number and are, for present purposes, unobjectionable. But in the discrimination structure the resultant behavior is described as approach-avoidance, whereas in transposition it appears as jumping to the left or right. Since, by definition, transposition follows discrimination without further training, and since discrimination is a requisite for transposition, it seems reasonable to expect and demand uniformity of the terms used in describing these interdependent functions. Perhaps expediency, or a desire to make the diagrams attractively simple, may have motivated the shift in basic terms. Diagramming discrimination in terms of left- and right-going responses would (according to my translation) require an increase of the theoretically minimum number of cells from 4 to 10. A structure accounting for transposition in approach-avoidance terms would necessitate no less than 28 cells with a great complexity of excitatory and inhibitory interconnections.[1] Of the two possibilities for obtaining consistency of descriptive terms, the latter seems preferable if not necessary: according to Householder's unmodified transposition structure, a shift in the spatial arrangement of the stimuli from left-right to up-down would result in complete loss of the habit. And if the subjects were forced to look at the stimuli from an upside-down position, they should now respond positively to the stimulus which was negative during training.

If an animal has learned a left-going response to the stimulus configuration WB, a right-going response to BW—if it has learned this and nothing more—then one would not expect consistent response [2] to W or B when the objects are presented one above the other: W/B or B/W. If, instead, the animal has learned approach to W, avoidance of B, little disturbance would be expected when the spatial relationship is

[1] This structure was worked out by Robert A. Blum and Josephine S. Blum of these Laboratories. In addition to the postulates used by Householder, it depends on precise timing relationships in the firing and refractoriness of the cells involved. The modified structure would account for complete transfer from the left-right to one other spatial arrangement (*e.g.*, up-down), but additional similar nets would be necessary to permit consistency of response when the stimuli are placed in still other relationships.

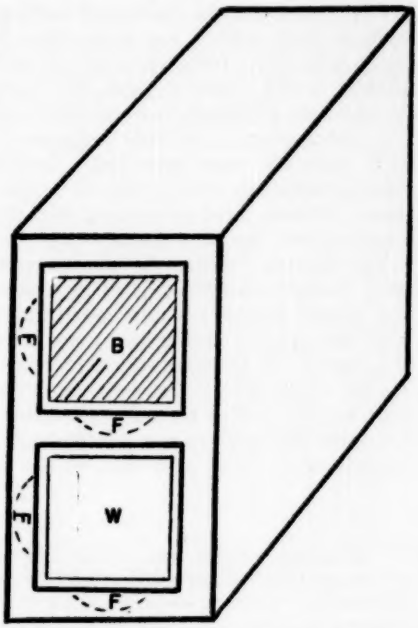
[2] Except, possibly, on the basis of a residual preference, present before training began, for W or B.

thus changed.[3] (Any minor disturbance that *did* occur might be referred to one of several "extrinsic" factors: emotional upset following change in a familiar situation, shift in the habitual motor pattern, and so on.) The specific aim of the following experiment was to determine whether chimpanzees, trained in a given discrimination habit with the stimulus-objects in one spatial arrangement, then respond indiscriminately or consistently (to the previously rewarded object) when the discriminanda are presented in an entirely different spatial relationship.

APPARATUS AND PROCEDURE

Two sets of stimulus-plaques were used: 1) a plain black (B) and a plain white (W) square surface; 2) a one-inch, black-edged red stripe, one running horizontally (H) and one vertically (V), each centered on a square tan surface.

The two plaques (black and white, *or* horizontal and vertical) were presented in a box-like holder shown in the figure. The subjects, reaching with their hands through the wire mesh or bars of the cage, made their choices by pushing the plaque backwards in the holder. This made accessible the food-well which was baited or not according to correctness of choice. A small piece of banana or apple was used as reward. The holder could be presented so that the plaques were above and below each other, as shown in the figure, or, by rotating 90 degrees, so that they were to the left and right of each other. Two sets of food-wells were available, as shown. The holder rested on a removable platform, fastened to the animal cage, and the distance of this platform from the floor



Representation of apparatus used for all learning and transfer trials. Position shown here presents stimulus-plaques B and W (black and white) in up-down relationship. Sheet metal edging (light inner lines) slightly overlaps stimulus cards, exposing a 4⅞″ square area. F = Food-well. Outside dimensions: 6½″ wide, 12½″ high, 9½″ deep.

was adjusted so as to provide minimum variation in height of the plaques when the holder was in up-down and left-right positions. During baiting and changing of the stimuli, the holder was drawn back, out of reach of the animal, and for response it was pushed up against the cage. The plaques were in place at time of baiting and the experimenter always reached towards *both* food-wells, from behind, in a uniform order. Other precautions, including the baiting of *both* food-wells, insured that the subjects were not responding on the basis of secondary cues. The correction technique was used, allowing a second response (following an error) a few seconds after the first one. An experimental session consisted of 25 trials and there was usually one session per day.

[3] The issue here under discussion is not directly concerned (a) with whether the cue is "spatial" or "non-spatial," nor (b) with the question as to whether the "absolute" or "relative" properties of the stimulus-objects provide the effective cue. The problem of describing the critical response as approach-avoidance or as discrete muscular movements remains, whatever may be the facts and their interpretation in respect to either of these questions.

Prior to any specific training or learning sessions, each subject was given from 8 to 16 adaptation trials in which he was allowed to take a piece of fruit from each of the four food-wells. A minimum of two, and a maximum of four responses to each food-well were permitted. During these adaptation trials "neutral" plain brown plaques were substituted for the stimulus-cards described above.

Ten animals (Group A) were trained on a discrimination habit (7 of them with the stimuli in the left-right positions, 3 with the up-down arrangement) and were then tested with the same stimuli presented in the other spatial arrangement. The tests were given after the subject had made not more than one error in two successive sessions of 25 trials each (*i.e.*, 49 out of 50 correct) with the initial set-up. It is to be noted that the subjects had had no prior *training*—at least in this experiment or with this apparatus—with the spatial arrangement used in the transfer tests. Depending on the accuracy of their performances, these animals were given from two to four sessions each (50 to 100 trials) in the transfer situation; *i.e.*, until they had again met the criterion of 49 correct responses in 50. Results are presented in Table 1.

Five chimpanzees (Group B) were trained on one discrimination habit in the left-right situation, on a different habit in the up-down arrangement, *before* being given any transfer tests. Having met the criterion of mastery (in this case 48 out of 50 correct) on the first habit (left-right

TABLE 1

Learning, transfer, and savings scores for animals tested on transfer to either up-down or left-right *before* having had any specific training experience with that spatial arrangement (Group A). Learning and transfer scores do *not* include sessions in which criterion was met.

Discrimination; subject	Learning		Transfer		Percentage savings	
	Trials	Errors	Trials	Errors	Trials	Errors
(1) Training left-right; testing up-down						
W *vs.* B						
Buff*	0	0	0	0	100	100
Dehn	125	34	50	9	60	74
Scarf	75	31	25	2	67	94
Ken	200	47	50	4	75	91
B *vs.* W						
Mars	75	43	0	0	100	100
Verb	175	58	25	5	86	91
Hank	125	44	50	15	60	66
(2) Training up-down; testing left-right						
W *vs.* B						
Nira	250	49	0	0	100	100
B *vs.* W						
Alf	75	22	0	0	100	100
H *vs.* V						
Wendy	400	117	0	0	100	100
Mean (N = 10)	125	40	20	3.5	84	91

W = White; B = Black; H = Horizontal; V = Vertical.

* See text for explanation of Buff's learning scores.

TABLE 2

Learning, transfer, and savings scores for animals trained on one left-right and one up-down discrimination before being tested for transfer to the alternative spatial arrangement (Group B). Learning and transfer scores do *not* include sessions in which criterion was met.

Discrimination; subject	Learning		Transfer		Percentage savings	
	Trials	Errors	Trials	Errors	Trials	Errors
(1) Training left-right; testing up-down						
W *vs.* B						
Bokar (1)	125	50	25	3	80	94
Alpha (1)	50	12	0	0	100	100
B *vs.* W						
Pati (1)	125	35	0	0	100	100
Wendy* (2)	50	8	0	0	100	100
V *vs.* H						
Don (2)	225	103	25	4	89	96
H *vs.* V						
Ami (2)	150	46	50	7	67	85
Alf** (2)	125	40	0	0	100	100
(2) Training up-down; testing left-right						
W *vs.* B						
Don (1)	125	37	0	1	100	97
Ami (1)	125	42	0	0	100	100
B *vs.* W						
Dina*** (1)	75	22	0	0	100	100
V *vs.* H						
Pati (2)	200	61	50	5	75	92
Bokar (2)	150	76	0	0	100	100
H *vs.* V						
Alpha (2)	200	78	0	0	100	100
Mean (N = 13)	133	47	11.5	1.5	91	97

W = White; B = Black; H = Horizontal; V = Vertical.

Figure in parentheses after subject's name indicates whether this was first or second habit learned.

* Wendy was trained in up-down *and* tested in left-right situation on H *vs.* V before this training on B *vs.* W was begun. See Table 1.

** Alf was trained in up-down *and* tested in left-right situation on B *vs.* W before this training on H *vs.* V was begun. See Table 1.

*** Dina had 225 trials on V *vs.* H in the left-right position, without meeting criterion or making progress, before the transfer tests on B *vs.* W were given.

for 3 animals, up-down for the other 2), they were trained, to the same criterion, on the second habit. Then a single session, consisting of 12 successive trials on each of the two habits—each in its original spatial arrangement—was given before the transfer tests were begun. (No animal made more than one error in these final 24 learning trials.) The tests were also given by the split-session method: 12 (or 13) trials on the first habit in its alternative spatial relationship, followed by 12 (or 13) trials on the second habit in *its* alternative arrangement, until the criterion of 48 correct trials on each was met. Two or more sessions of transfer tests were given each subject. Results are shown in Table 2.

Finally, two of the subjects of Group A (Alf, Wendy) were trained and then tested on a second habit after completion of training-testing on the first. The results are included in Table 2, since they represent transfer *after* experience (on a different habit) in the test situation. Included here also are the results of Dina who had received training, but had not reached the criterion, on a previous stimulus-pair (V *vs.* H) presented in the spatial arrangement (left-right) of the transfer tests of the second (B *vs.* W) habit.

RESULTS

Results obtained with the Group A animals, who were tested before they had any training experience with the spatial arrangement of the specific transfer situation here used, are presented in Table 1. Data of the Group B subjects, tested after experience with the transfer situation but in connection with a different stimulus-pair, are given in Table 2. In 10 of the 13 cases included in Table 2, the subject was tested "simultaneously" on each of two discriminations presented for transfer in a spatial arrangement other than that used during the original learning.

The savings scores are large in all cases and give convincing evidence for a high degree of transfer from the left-right to the up-down situation and *vice versa*. In 13 of the 23 cases (Tables 1 and 2) transfer was complete and immediate (no errors). (Since the criterion of mastery is based on performance *within* sessions of 25 trials, the scores usually show greater savings in errors than in trials.)

The data indicate that the V *vs.* H and H *vs.* V habits are more slowly learned, and produce more errors in transfer, than the W *vs.* B and B *vs.* W habits. No consistent differential effects of spatial arrangement (left-right *vs.* up-down) are seen in the learning scores. There is a suggestion that transfer from left-right to up-down may be a little more difficult than the reverse; this could be explained by the fact that all subjects had had previous experience (in other experiments) with the left-right but not with the up-down placement of two choice-objects.

Transfer errors seem to be associated with emotional tension and perhaps with age. Four of the subjects were about 3 years old: Verb, Dehn, Hank, and Buff; all were exceptionally tense and three of them contributed the largest transfer error scores in Table 1 (5, 9 and 15 errors, respectively). All other subjects were from 7 to about 30 years old, and among these the worst transfer scores were contributed by notably tense individuals (Bokar, Pati, Don, Ami), some of whom perhaps associated this apparatus with a rather similar one in which they recently had received electric shock.

The performances of Buff and Hank deserve special mention. At the age of about six months, soon after they were able to walk, each of these animals was trained in a discrimination habit. The experimental set-up was quite different from that of the present study, requiring locomotion to the left or right, depending on which of two adjacent, curtained passage-ways was marked with a white and which one with a black stimulus-patch. Buff had mastered a white *vs.* black, Hank a black *vs.* white habit. (Note that these are the same stimulus-values shown in Table 1.) The present study was done approximately 25 months after their last previous experiences with this earlier situation. It seems clear that Buff had retained the effects of his early training over this two-year interval; he responded to white without exception in both learning and training trials. Hank chose black in 21 of the first 25 trials, suggesting considerable retention. During the next 3 sessions, however, he became very jittery and made chance

scores, after which he improved rapidly. In the first transfer session Hank made 13 errors, in the second session only 2.

Four of the subjects had had brain operations some two years before: prefrontal removals in the case of Scarf, Mars, and Nira, prefrontal lobotomy in the case of Ken. The transfer scores of all four animals are within the range of the other subjects. Ken and Nira were exceptionally slow in learning W *vs.* B; in both cases there was a long plateau in the learning curve at about the 85 per cent level of accuracy.

DISCUSSION

The specific question raised at the beginning of this paper has received a clear-cut answer: The fact that a visual discrimination habit learned in one spatial arrangement showed little or no disturbance when the stimulus-objects were presented in a quite different positional relationship indicates that the original performance must be described as approach to (or avoidance of) absolute or relational visual properties of the stimuli, rather than as two discrete movements, differentially elicited by each of two distinct total configurations. The perfect transfer scores of Mars, for instance, are explicable if we describe his learning diagramatically as

$$S_{black} \rightarrow R_{approach} \qquad S_{white} \rightarrow R_{avoidance}$$

but not if we describe it as

$$S_{black\text{-}white} \; R_{left} \qquad S_{white\text{-}black} \; R_{right}$$

This finding does not exclude the possibility that *both* sets of connections or associations were established during the learning period, but it does show that approach-avoidance was independently effective. The present results pertain to particular chimpanzees with certain background experiences, observed in a specific experimental situation, and tested after a given amount of overtraining. How generally they may hold under other conditions remains to be discovered. The results obtained are consistent with common sense—to the layman the present study must appear as another demonstration of the obvious—and also with some earlier experimental work (8) which suggested that the critical differentiation in visual delayed response is of the external field rather than of the required muscular responses. Nevertheless, we must also take into account the fact that *some* discrimination responses (see introduction) are more directly describable in terms of discrete movements.[4]

Logically there seem to be three possibilities: 1) By extensive experimentation the immediate appropriateness of one or the other descriptive formulation may be determined for various animal forms, various discrimination situations, differing degrees of mastery, and so on. Whatever analogical or other explanatory conceptualization is adopted would,

[4] In this paper we are dealing with the establishment of a "preference" for one of two stimulus-objects, or of consistent differential movements to differing stimulus-situations, in organisms with certain potentialities and associations already given innately and/or by previous experience. Chief among these prerequisite and taken-for-granted behavioral characteristics are (1) differential effects on the nervous system of the discriminanda, *i.e.*, discriminability of the pertinent stimuli; (2) "object-" or "thing-perception," such that a given object elicits the same perception under varying conditions or contexts (*e.g.*, of distance, illumination, background); (3) sensory-motor coordinations such that a given perception does (or through experience may come to) evoke a response which is always "the same" *in reference to* (a) the spatial relationships of organism and object (*e.g.*, the animal makes appropriate muscular movements to approach food, regardless of whether the food is to the left or right, near or far), or (b) its own bodily relationships (*e.g.*, if its right arm is broken, it now scratches the same itchy spot with its left hand). Any attempt to trace the origins of such features of behavioral adjustment in our discrimination-experiment subject is beyond the scope of the present discussion.

of course, have to be consistent with the applicable descriptive categorization. It seems probable that, for the higher organisms at least, *both* of the binary classifications considered in this paper would find application, according to the nature of the discrimination situation in question. On the explanatory level, this might necessitate the postulation of two distinct mechanisms for discrimination within the same individual. 2) It may be that a new binary or multiple classification can be found which would comprehend all the empirical data here grouped under one of two distinct sets of descriptive terms. That is, the distinction between approach-avoidance and discrete, orientational movements, may not be "real." If such a synthesis were made on the descriptive level, a single inclusive explanatory conceptualization would account for all the pertinent facts considered in the present discussion. 3) Perhaps one of the two binary classifications considered in this paper can be "reduced" to the other, can be shown to be a special case of the second one. This solution likewise would have the advantage of making possible the explanation of all two-choice discrimination learning by a single mechanism.

The remainder of this discussion will examine the third one of the aforementioned alternatives. I shall try to suggest how the kinds of discrimination learning which at first thought do not seem to fit the approach-avoidance formulation, may nevertheless be appropriately described in those terms. The first step will be to see if the distinction between our two sets of terms can be sharpened.

The term "approach" is, by itself, meaningless; it calls for a supplementary statement of what is being approached. Avoidance, likewise, is avoidance *of* something. That something is usually an object, a region or a condition of the environment, frequently called the goal. Approach and avoidance, therefore, are terms used to describe an act, or goal-directed behavior.

Left-going and right-going, by contrast, are descriptions of movements, without essential reference to the environment or to the effect of the movement. This part (of the body) moves, or that part; this part flexes or extends; the body as a whole turns on its vertical axis leftwards or rightwards.

We must here digress briefly in order to avoid a deceptive semantic confusion. Any description of response which makes essential references to the environment (to a goal) is description of an act to which the approach-avoidance formulation applies. This is true even when, as a short-hand convenience, we speak of the subject as "going to" or "manipulating something" which is designated by its spatial characteristics—*e.g.*, as being to or of something on the left side of a specific environment. Consider the type of experiment in which an animal is required to respond to one or the other of two places (visually similar boxes, doors, buttons) in accordance with stimuli having no differential spatial characteristics. Auditory problems (in which the subject must respond to the left for one sound, to the right for a different sound) and T-maze studies in which rats are trained to make one turn when hungry, the opposite turn when thirsty, are examples. Although the response-objects may be visually very similar or identical, they are usually differentiable exteroceptively by one or both of the following types of cue: a) background features, including direction and distance from conspicuous objects such as lights and windows; b) kinaesthetic stimuli resulting from orientation in respect to background features or in respect to initial posture based on a constant point of entrance to the experi-

mental situation. Here the response is described with reference to the environmental situation. If, on the other hand, the response is described only as a given muscular contraction or movement, with no consistent and necessary effect on the organism-environment relationship, the approach-avoidance formulation is no longer directly applicable.

On first thought, increased respiration rate, salivation, or hand-clapping appear to be descriptions of response in terms of "pure" movement. There is no obvious goal-object or altered organism-environment relation, and most acts *are* describable in those terms. A broader and more generally applicable criterion of the act, however, is that of a response having a given consequence or effect. The salivary response may be thought of purely as a secretory activity, but it may also be conceived of as the production of saliva. Hand-clapping is a muscular coordination, but it results in cutaneous, kinaesthetic, and auditory sensations. This point will be discussed further below.

In the auditory problem mentioned above, the a- and b-type cues, differentiating the response-objects exterocĕptively (*i.e.*, by reference to the environment), are not sufficient to solve the problem; it is the spatially neutral stimulus of sound X (rather than sound Y) which determines that response should be to the left rather than to the right. One may, therefore, conceive of the cue as consisting of a complex stimulus or stimulus-pattern:

$$\left.\begin{matrix} S_L \\ S_X \end{matrix}\right\} \rightarrow R+ \qquad \left.\begin{matrix} S_L \\ S_Y \end{matrix}\right\} \rightarrow R-$$

$$\left.\begin{matrix} S_R \\ S_Y \end{matrix}\right\} \rightarrow R+ \qquad \left.\begin{matrix} S_R \\ S_X \end{matrix}\right\} \rightarrow R-$$

where S_L and S_R designate the exteroceptive cues differentiating the alternatives, left and right, and R+ and R− represent approach and avoidance (or, response and no response), respectively. Or one may say that a conditional response is required: If S_L and S_X, then R+, but if S_L and S_Y then R−; if S_R and S_Y, then R+, but if S_R and S_X, then R−. The fact that such problems are in general learned with relative difficulty, is in keeping with this interpretation. The fact that response is precisely to a box (or door, or button) and not to the usual or approximate location of the box, even when, as in an experiment on spatial delayed response with chimpanzees, (4) the containers are surreptitiously moved closer together or further apart, is not a critical argument, but it is more directly accounted for in terms of approach-avoidance than of specific muscular movements which have no reference to a goal or effect.

Up to this point our discussion has been confined to the two-choice discrimination situation. The same considerations apply in principle to the multiple-choice situation, where selection of one box (or door or path) of three or more, on the basis of spatial relationships or visual characteristics, is required. As a matter of fact, choice of the one positive, from among eight closely spaced, similar negative alternatives, would require rather extreme precision of the differential movements being learned to each of nine stimulus concatenations, and presumably would involve an increase of difficulty which is not borne out by experimental data (6). If the eight negatives were all different, the subject would have to learn nine responses, each of which could be elicited by 40,320 stimulus configurations! If, on the other hand, the subject has learned approach to the positive, avoidance of the negative, increasing the number of negative objects should not appreciably affect difficulty of the problem.

"Successive" discriminations, in which only one (of the to-be-discriminated stimuli) appears at a time, offer no additional problem in the present context. Usually the subject is required to make, or not to make, a certain response, and this may be described in approach-avoidance terms:

$$S_X \rightarrow R+ \qquad \text{and} \qquad S_Y \rightarrow R-.$$

When the response must be differentially oriented in accordance with spatially differentiated stimuli (*e.g.*, pressing the left

key when a light is flashed on the left, the right key when it flashes on the right), the behavior is appropriately described as approach to the lighted (and avoidance of the nonlighted)side. And if discrete movements are required to stimuli which are not themselves spatially differentiated (very few instances of this problem have been reported in the literature), the interpretation of a compound stimulus or conditional response is applicable: a yellow light, for instance, in combination with certain background and/or kinaesthetic stimuli, requires approach; a blue light in combination with the same exteroceptive stimuli demands avoidance.

There are some instances of discriminative behavior which fit the approach-avoidance formulation (or variations thereof, such as response *vs.* no response, or positive *vs.* negative response) but seemingly have no goal-reference; the response does not obviously alter the organism-environment relation. The salivary response in classical conditioning would be an illustration of this. There are other instances which have no goal-reference and which, offhand, seem to be describable only in terms of differential movements of various muscle groups: Thorndike's cats and monkeys which were rewarded for assuming nonsensical postures (**12**), Skinner's superstitious cage-pacing and hopping pigeons (**11**), and Schiller's head-patting chimpanzee (**10**). There is a certain degree of discrimination here; the response, being a part of the animal's repertoire of "spontaneous" behavior, may occur at any time, but is given more frequently under certain conditions: in the presence of the experimenter, or in a particular cage or apparatus. In order to provide an extreme case, we may extrapolate from this sort of behavior to the imagined instance of an animal which has learned to twitch its nose for one stimulus, its tail for a different stimulus.

In order to describe these latter discriminative responses as acts, we must apply our more general criterion, namely that of a consistent consequence or effect. (Probably all the aforementioned responses have distinct sensory consequences—even when, for instance, the saliva does not reach the mouth. It has been reported that skeletal conditioning does not occur in the curarized animal, **2**). Patting the head is comparable to pushing the red plaque; after training, the ape does not sometimes pat its belly, and if one hand is occupied in holding a piece of food, the other hand is used to produce the same result. The response is defined in terms of its effect. Stimuli are discriminated, not responses. For our hypothetical extreme case we must include local signs among the stimuli which may determine a discriminative response. A local sign presumably has an already established connection with motor centers controlling movement of the same bodily region. With S_N and S_T representing local signs for nose and tail, respectively, the diagrammatic representation of nose-twitching for red (S_R), tail-twitching for green (S_G) becomes

$$\left.\begin{matrix} S_N \\ S_R \end{matrix}\right\} \rightarrow R+ \qquad \left.\begin{matrix} S_N \\ S_G \end{matrix}\right\} \rightarrow R-$$

$$\left.\begin{matrix} S_T \\ S_G \end{matrix}\right\} \rightarrow R+ \qquad \left.\begin{matrix} S_T \\ S_R \end{matrix}\right\} \rightarrow R-.$$

The conditional response is "twitching," and whether the nose or tail twitches depends on the particular combination of external and local-sign stimuli.

CONCLUSIONS

The logical necessity, in some instances, of describing the discriminative response as an act, that is, in terms of its consequence or effect (usually with reference to a goal or an altered organism-environment relationship), is illustrated in the ape experiment reported above. Description in terms of movement, without reference to the environment, does not account for the prompt transfer shown by sixteen chimpanzees. There is no conceivable "equivalence" or "family relationship" in either the stimulus-situation—white-black, black-white and $\frac{\text{white}}{\text{black}}, \frac{\text{black}}{\text{white}}$—, or in the movements—left, right and up, down—which accounts for the generalization.

I have tried to show the applicability and adequacy of the approach-avoidance formulation for a wide variety of

discrimination situations, including successive discrimination and problems requiring selection from multiple alternatives. For certain types of problem we have had to conceive of the behavior as involving a conditional response—a response determined by a complex stimulus, or by the "simultaneous" effectiveness of two independent cues. In one extreme hypothetical case local signs have had to be included among these effective stimuli. The plausibility of these assumptions is supported by the experimental finding that such problems are relatively difficult, and are learned slowly.

The approach-avoidance formulation more adequately accounts for the precision of response, especially when positions of the choice-objects are varied slightly, than does description in terms of learned movements. It makes unnecessary a second, supplementary mechanism (which presumably would have to be an approach-avoidance type of mechanism) to account for final correction and adjustment after the critical learned movement has brought the subject (his body or his hand) nearer to the correct object. It offers a single, uniform, consistent set of descriptive terms for discriminative behavior. The desirability for subsequent theoretical elaboration, of such uniformity at the descriptive level, was discussed at the beginning of this paper.

The integrations which provide (a) perceptions—of things, of direction, distance, and so on—and (b) the muscular and sensory-motor coordinations of locomotion and manipulation, are either innate or have been acquired in earlier ontogeny. With the origins of these basic organizations we have not here been concerned; we have taken these units of integration for granted. Since such perceptions and sensory-motor coordinations are already available, it would appear a great deal more efficient and effective for the organism to take advantage of them,—more efficient because establishment of one or two associations suffices,—more effective because object-approach has wide generality. A learned movement, on the other hand, has by definition no consistency in reference to a goal or effect.

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